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Book of Abstracts

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PREFACE

You are welcome to the 14th International Riga MHD conference hosted by the Institute of Physics of the Latvian Academy of Sciences and the Latvian National Committee of Mechanics. The author index includes 373 scientists affiliated to 113 Institutions from 20 countries, 192 abstracts have been presented. Thank you for such a confidence in the vitality of the Riga MHD school!

All the previous 13 conferences played an indisputable role in making MHD a self-consistent scientific domain.However they could not be considered as truly international, remaining practically unattainable for the main part of the world. As an international success, a milestone in the course of Riga meetings, the IUTAM Symposium on "Liquid Metal MHD" held in 1988 must be mentioned.

Let us hope that the 14th Riga Conference will remain in our minds not only as a occasion for fruitful professional discussions. It could become an important organizing event, too, since it is planned to launch officially the "International Association for MHD and EPM" under the cover of IUTAM. We all must be satisfied that MHD has established close relations to such a promising neighbouring branch as Electromagnetic Processing of Materials (EPM). In the same time we must remember that the abbreviation "MHD" itself describes a field, compact in its deeper sense, but formally still torn to pieces. And mainly because of domestic ambitions, inherited from the past, often egoistic and badly substantiated! Let us join our efforts and voices to the consolidation of our research field in the crossing point of thermo-hydro-, and electrodynamics! We would be very happy if these, generally speaking, old ideas could reach a development during our conference.

Oļģerts Lielausis
Director,
Institute of Physics, Riga, Latvia

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Section A.
LIQUID METAL MHD

Theoretical and General Aspects

NUMERICAL SIMULATION OF A DOUBLE MHD ROTATOR EFFECT ON HYDRODYNAMICS AND HEAT TRANSFER IN A CYLINDRICAL VESSEL

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The efficiency of a double rotator employment for the transfer process intensification and widening of possibilities to control the characteristics of hydrodynamics and heat/mass transfer in a cylindrical vessel with a conducting fluid has been experimentally proved in [1]. The present paper proposes a mathematical model of the above MHD effect on the melt and discusses the results obtained on the model for calculation of hydrodynamic and heat characteristics of a flow at different ways of its generation. The model considers two inductors of a rotating magnetic field (RMF) placed co-axially in some distance to each other and around a cylindrical vessel filled with a conducting fluid. The magnetic fields of the inductors rotate in opposite directions. The fluid in the cylinder with walls of arbitrary conductivity can be confined from above and below by one or two rigid edges with arbitrary conductivity as well. The model provides an opportunity to calculate at different geometrical ratio of the "container with melt – RMF inductors" system and different physical characteristics of the rigid walls confinding the fluid.

A distinguished feature of the problem is its three-dimensionality at calculation of distribution of electromagnetic fields and, correspondingly, electromagnetic forces regardless of axial symmetry of each of the inductors and the fields generated by each of them separately. This situation is expressed through the dependency of the electromagnetic field distribution in the fluid on azimuthal angle φ, and is the result of a standing wave formation between two, travelling opposite each other, waves of the electromagnetic field. Special calculations have shown that in most practically important cases the dependence of the force on φ can be neglected since it does not significantly affect the azimuthal velocity dictribution in the melt.

The model under discussion helped to study the effect of a double MHD rotator on flow velocity patterns in cylindrical vessels with unconducting and conducting side walls and edges, which confind the fluid from below and above as well as at the presence of a free surface in the volume. In every case the distance between the inductors changes as well as their location with regard to the central plane of a liquid volume. The hydrodynamic calculation has been done according to the technique presented in [2]. The data obtained prove that employing the double MHD rotator it is possible to create various velocity patterns in a cylindrical liquid volume. These velocity patterns are characterized by formation of hydrodynamic shear layers (with rather large velocity gradients) in the plane, where the field rotation direction changes.

Assuming the results on the flow hydrodynamic characteristics, the paper also investigates the effect of the above MHD action on heat transfer and temperature field distribution in the fluid at a priori given temperature profile on a cylindrical vessel wall. It is shown that the range of the heat transfer parameter control in a fluid turns significantly wider, when the double MHD rotator is used. It is also determined by a number of design parameters in real devices.

References. 1. Sorkin M.Z., Mozgirs O. Magnitnaya Gidrodinamika, 1992, No.2, p.111-114 (in Russian). 2. Abricka M., Gelfgat Yu.M., Krūmiņš J., Priede J. In: Proc. of the 2nd Intern. Conference on Energy Transfer in MHD Flows, France, Aussois, 1994, vol.1, p. 253-257.

INSTABILITIES OF ANISOTROPICALLY DRIVEN DEVELOPED TURBULENCE IN D-DIMENSIONAL SPACE

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Deviation of the turbulence from isotropy in the realistic developed turbulence has been confirmed by a variety of laboratory experiments and computer simulations. It may be caused by the presence of specific initial or boundary conditions, interactions of fluctuating fields with mean flow gradients or some external fields.

The object of the study reported here is the reformulation of the functional statistical concept, which is often used to describe strongly developed turbulence of incompressible fluids. The purpose of the present work has been a generalization of the functional model for developed hydrodynamic and MHD turbulent systems with arbitrary level of anisotropy to d-dimensional case. An initial important motivation of the present work comes from the study of weakly anisotropic stochastic MHD [1], which suggested to us that even small anisotropy of forcing has significant qualitative influence and leads to destabilization of the usual kinetic regime. To obtain a universal description of developed turbulence, an anisotropic stochastic forcing has been introduced, which replaces both the initial and the boundary conditions in the Navier Stokes equation. Having carried out necessary calculations, we have determined a set of equations for scale - dependent effective variables, which allows the investigation of the stability of the kinetic regime.

Our study of long-range correlations in the anisotropic strongly turbulent hydrodynamics with the use of the method of perturbative field - theoretic renormalization group has the following implications: (i) for a thorough description of the large scale dynamics of the fluctuating velocity field it is necessary to consider new dissipative terms, which correspond to anisotropic turbulent viscosities and specific energy loss mechanisms; (ii) systematic investigation of the weak anisotropy limit and continuation of the space dimension d to nonintegral values shows that a stable universal kinetic regime with finite renormalized effective variables may occur at Euclidean dimensions $d_c < d \leq 3$ where $d_c = 2.68$. More interesting perhaps would be a general study of systems with higher degree of anisotropy, which could lead to corrections in d_c. Generalization of this treatment to MHD is straightforward.

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ASYMPTOTIC FLOWS IN NON UNIFORM MAGNETIC FIELDS

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The motion of an electrically conducting fluid in the presence of a permanent magnetic field is analysed. We consider a steady flow, whose magnetic Reynolds number is very small and whose interaction parameter is large: the magnetic field is considered as undisturbed and inertia as negligible. A known non electromagnetic body force, **f**, is supposed to act on the fluid as previously studied [1] in the case of uniform magnetic fields.

Then, an asymptotic analysis of the flow structure is performed, for any non uniform magnetic field in both the core region and Hartmann layers. The use of a curvilinear frame of reference, adapted to the magnetic field, is well suited to perform the analysis. Instead of the classical vector formulation, differential forms provide a useful tool in these general curvilinear coordinates. An analytical integration of the governing equations is carried out along the magnetic field lines. This study may be seen as a generalization of the work of Kulikovskii [2] who considered a similar problem with **f**=**0**. At this point, the hydrodynamical problem often remains untractable, but we show that existing symmetries in terms of cavity geometry, body force, magnetic field and boundary conditions, may lead to interesting simplifications. A particular symmetry, we refer to as the "singular symmetry", leads to a drastic simplification for the asymptotic structure and asymptotic solutions can easily be derived.

The theory is applied to some MHD flow configurations. A pressure driven flow in a bend is analysed (in this case, **f** equals zero). Then, some crystal growth configurations are investigated: in the Boussinesq approximation, the term of buoyant force is a given body force that the theory can handle. This force is not curl-free and asymptotic results show large departures from the pressure driven ones. One of the most interesting results is that the kind of symmetry for a configuration governs the flow structure rather than, e.g., the electrical conductivity of the walls.

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BOUNDARY PROBLEMS OF MAGNETIC HYDRODYNAMICS IN SELFCONSISTENT FORMULATION

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At present time the problems of magnetic hydrodynamics and investigation of the movement of the ionized medium taking into account their interaction with the electromagnetic field acquire cognitive and technical meaning. In many applications the boundary S or its part of the area of the continuous movement of the unbroken medium is unknown beforehand and must be determined. In this work the integral approach to the solution of the boundary problems of linear magnetic hydrodynamics in a laboratory coordinate system, in which the surface of the discontinuity moves under the action of the falling field is considered. That is the problem is stated in selfconsistent formulation.

If the main equations of magnetic hydrodynamics are formulated in an integral form, in which the continuity of the unknown functions, as a matter of fact, is not meant and which are more general in the discription of the discontinuity processes, than the building of the sectionally smoth solutions for the differencial equations results in the theory of the generalized functions (distributions). In this case the satisfuction of the boundary and initial conditions occurs at the formulations of the problem automatically.

In the approximation of the ideal magnetohydrodynamics the behaviour of MHD medium is defined by Maxvell's equations, along with Ohm's law and continuity equations of motion, mass and energy. The system of the linearizated differential equations in respect to the deflexion of the magnetic field b, velocity u from its balance values $(B_i, 0)$ is the basis of the report:

$$\nabla^2_{Si}\, grad\, div\, u - \frac{\partial^2 u}{\partial t^2} + \left[rot\frac{\partial b}{\partial t}, \frac{B_i}{4\pi\rho_i} \right] = 0,$$

$$rot\left[u, B_i\right] - \frac{\partial b}{\partial t} = 0. \qquad (1)$$

In arbitrary medium with the parametrs, described by the continuous functions. It is necessary to complete the system (1) by boundary conditions on the surface of the discontinuities while considering discontinuity solutions. In the particular if the surface of the discontinuity in the considered coordinate system rests the system of the boundary conditions following from the continuity of the streams of mass, energy, impules, tangential components of the electrical field and a normal component of the magnetic field is of the following form:

$$\{\rho u_n\}=0,\ \{\pi_{in}\}=0,\ \{W_n\}=0,\ \{E_\tau\}=0,\ \{B_n\}=0. \qquad (2)$$

However under small perturbation in the general case it is necessary to take into consideration the deformation and additional velocity of the surface of the discontinuity. In this case the boundary conditions are written in a laboratory coordinate system in which the sutface of the discontinuity moves along the normal to the surface S with velocity u_s; there with it is necessary to substitute un for $u_n - u_s$ every where in the boundary conditions (2).

To deduce the integral equation in the laboratory coordinate system let us use the tenzor Green's function, which was found in [1]. In this case the boundary MHD problem is formulated at first in a differential statement in the space of the generalized functions. This allows to include the conditions for the field functions on the surface of the non-uniformity in the equatuions. Then by means of the fundamental solutions the boundary problem is reformulated into the form of the integral equations, which include the boundary conditions and own the physical clearness (the extinction theorem works). All this allow to develop the algorithm of the solution of the problem. The obtained equations are a composition in the space of the generalized functions, that will essentially simplify taking into account singularities of the equations under the integral sign.

The developed algorithm of solution of the selfconsistent boundary problem was demonstrated as en example of entering the packet of plane monochromatic MHD waves

$$u(r,t) = \sum_{j=1}^{3} u_j \exp[-ik_j r + i\omega t]$$

into homogeneous MHD medium occuping self space $z=0$ and defined by the parametrs (V_{A2}, V_{s2}, B_2).

It has been shown that not only reflection, refraction laws follows from the extinction theorem in magnetor hydrodynamics in a logically closed form as well as the amplitudes of all the waves diverging from the boundary are found, but the boundary deformation S can be determined, that it is possible to finde a normal component of the surface distortion velocity.

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MAGNETOHYDRODYNAMIC FLOWS AT FLOODED PLANE JET RUNING INTO HALF-SPACE IN A STRONG MAGNETIC FIELD

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Studying of MHD flows at flooded plane or round jet running into half-space filled with the same fluid, is usually restricted by the case, when either width or radius of the split, through which the fluid runs into half-space are neglectively small (see [1], [2] and it's referencies). In this paper the exact analytical solution for the problem about flooded plane jet running into half-space through the split of finite width in a sloping uniform magnetic field at Stokes and inductionless approximations is obtained. Asymptotic solution of this problem at Hartmann number $Ha \to \infty$ in two particular cases is obtained. The fluid is located in region $y > 0, -\infty < x, z < +\infty$. The plate is situated on the plane y=0 and have a split in a region $-1 \le x \le 1, -\infty < z < +\infty$. The fluid with constant velocity $v_o \vec{e_y}$ flows through this split. External magnetic field

$$\vec{B_e} = B_o \vec{e_x} \cos\alpha + B_o \vec{e_x} \sin\alpha \qquad (1)$$

is directed under angle α to the split. In dimensionless quantities the problem have the following form:

$$-\frac{\partial P}{\partial x} + \Delta v_x + Ha^2 A \sin\alpha = 0; \quad -\frac{\partial P}{\partial y} + \Delta v_y + Ha^2 A \cos\alpha = 0 \qquad (2,3)$$

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0; \quad A = v_x \sin\alpha - v_y \cos\alpha, \quad \Delta = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2} \quad . \qquad (4)$$

The boundary conditions are the following:

$$y = 0: \quad v_x = 0, v_y = \left\{ \begin{matrix} 0, x \notin [-1, 1] \\ 1, x \in [-1, 1] \end{matrix} \right. ; \quad v_x, v_y \to 0 \quad at \quad \sqrt{x^2 + y^2} \to \infty. \qquad (5)$$

The analitical solution of problem (2)-(5) using Fourier transforms with respect to variable x is obtained. In the case of parallel external magnetic field (at $\alpha = \frac{\pi}{2}$) the velocity's component v_x is obtained in the form:

$$v_x(x, y) = \frac{v_o}{\pi} y \sinh \mu y \left[\frac{K_1(\mu\sqrt{y^2 + (x-1)^2})}{\sqrt{y^2 + (x-1)^2}} - \frac{K_1(\mu\sqrt{y2 + (x+1)^2})}{\sqrt{y^2 + (x+1)^2}} \right], \qquad (6)$$

where $\mu = 0.5Ha$, $K_1(z)-$ Macdonald's function and velocity's component $v_y(x, y)$ and pressure P(x,y) are reduced to integrals of function $K_1(z)$. Analysis of the obtained solutions shows that at $Ha \to \infty$ the flow consists from the following boundary layers: the region $-1+l<x<1+l$, $0<y<O(Ha)$, $l = 2(y/Ha)^{1/2}$, where $\vec{v} = \vec{e_y} = const$; the regions $|x-1|<l$ and $|x+1|<l$, where velocity $\vec{v}$ changes from $\vec{e_y}$ to 0; the far field $Ha \le y \le +\infty$ and the regions of stable liquid (v=0) $x + 1 < -l$, $x - 1 > l$. Asymptotic of pressure force F_p at the entrace of the split is equal to $F_p = 2Ha, Ha \to \infty$. Analogous asymptotic solutions were also obtained in the case of transverse magnetic field (α=0). In this case Asymptotic of pressure force at the entrace of the split is equal to $F_p = \frac{16\sqrt{2}}{3\sqrt{\pi}} Ha^{3/2}$.

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ROTATING ELECTRICALLY INDUCED VORTICAL FLOW WITH FREE SURFACE

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The rotating electrically induced vortical flow over a single infinite rotating disc with free surface has been investigated in Karman's similarity solution class. The divergent electrical current passes from the rotating disc to the free surface.

The influence of convergent and divergent flows, which are created by electrical current, on the rotation velocity of liquid has been discovered. The convergent flow at the rotating disc intensifies the rotation movement of free surface several times. To define the influence of electrical current strength on the rotation velocity the following experimental model has been created.

In the horizontally placed cell (having diameter 265 mm and high 50 mm) the copper electrodes, one of which is a surface of cell side walls and second placed in the center of cell bottom, have been mounted. The disc (having diameter 260 mm) made from Plexiglas with copper insert (having diameter 50 mm) was also placed in the cell. The disc was rotated by reversible electric motor providing the rotation of disc with angular velocity 2 revolution per minute (RPM). The cell was filled with mercury up to high equal 40 mm. The current from generator (6V, 1000A) passed in the following way: from central electrode to copper insert of disc, then further through the space between electrodes (mercury) to the surface of side walls of the cell.

The purpose of the experimental modeling was to determine the influence of electric current strength on the rotation velocity of mercury. The measurements were carried out on the free surface of mercury using graphite particles tracks. The time of full revolution of the particle around the axis was fixed and average value from ten observations was gained. As it follows from the experimental results, at the absence of electric current the working fluid (mercury) is rotating as a solid body with the velocity equal to the rotation velocity (2 RPM) of disc. When electric current passes through the working space, in the region of copper insert of disc the rotation velocity of mercury increases sharply reaching value 20 RPM at current strength 1500A. As we can see from experiment, the rotation velocity of mercury in the region of copper insert increases ten times. In the rest part of free surface in the cell the gradual diminishing of angular velocity up to the 2 RPM at the side walls was observed .

ELECTRICALLY INDUCED VORTICAL FLOW BETWEEN TWO PARALLEL ROTATING DISCS

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The flow, which arises between two infinite rotating discs, has been investigated. The divergent electrical current passes downward to the lower electrically non conducting disc. The discs are rotating with different angle velocities both in the same and opposite directions. The problem has been examined in Karman's similarity solutions class. In this class the formulation of problem is reduced to the solving of system of ordinary 6th order differential equation, in which we have two defining parameters: Reynolds number Re and electrical current parameter S. The analytical solution of formulated problem is being searched in the form of double-series expansion using this parameters.

The received solution for the first seven terms of this expansion series can be considered valid for $Re<10$ and $S<1000$. For receiving the solution at higher values of parameters Re and S the numerical integration of system have been used.

For numerical integration ordinary system Runge-Kutta-Fehlberga method with automatic choosing integration step according to needed precision has been applied. For the finding missed boundary condition Newton's method was used. The solution for high values of Re and S was calculated by method of step-by-step increasing of this parameters. As a first boundary conditions approximation for the first step the analytical solution was used, for the next approximation - the boundary conditions defined at previous step. At finding the solution by this way the bifurcation of solution have been discovered, depending on the method by which the required rotation at fixed values of Re and S have been gained.

The influence of convergent and divergent flows, which are created by electrical current, on the liquid rotation velocity have been discovered. The convergent flow created by electrical current intensifies the rotation movement several times. More over, at parameter S increasing the trend of maximal velocity move to the upper disc.

At parameter Re increasing the formation of boundary layers at both discs heave been detected. When one disk is at rest, or both discs are rotating in the same direction, the flow at high Reynolds number can be represented by compounding two one-discs solution. There are boundary layer attached to both discs and in the main body of the fluid, the flow is from the slower to the faster disc. When the discs rote in opposite directions, the flow is much more complicated. At high Reynolds number appear a strong radially inward flow near the faster discs. This gives a boundary layer whose thickness is proportional $Re^{-1/2}$, attached to the faster disc, and the axial velocity is from the faster to the slower disc over the main part of the region between the discs.

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ASPECTS OF MHD IN SEA WATER

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MagnetoHydroDynamics is a well known mean to thrust directly a ship in sea water without propeler and mobile mechanical part. The combined action of a magnetic field and electric field produces a **JxB** forces field with a very large variety of topology depending on magnet and electrode geometry. Sea water is an electrolyte, thus applying current via electrodes produces an undesired electrolysis. Consequently three kinds of phenomena take place in a sea water thruster: hydrodynamics, electromagnetics and electrochemistry. The following presentation aims to present two aspects of MHD seawater thruster.

The first aspect concerns external MHD propulsion which consist to thrust the ship with a **JxB** field produced by electrodes and magnets placed circumferentially around the hull. The forces field is strongly non uniform and it modifies the turbulent boundary layer surrounding the ship. A model is presented and justified. It couples a diametral (r, θ) 2D finite difference electromagnetic solver with an axial (r,z) 2D finite difference fluid mechanic solver. Some results are presented which demonstrate the modification of the turbulent boundary layer under the action of a strongly non uniform **JxB** field.

The second aspect concerns seawater electrolysis. The only reaction possible on the cathode is hydrogen oxydation, on the anode both oxygen and chlorine reduction are possible. In each case, the total amount of gas produced is well known (Faraday's law) but the evolution of the voltage drop and the gas distribution depending on the flow (turbulent boundary layer) are very difficult to predict. An experiment of our laboratory (LEGI-IMG) is devoted to the analysis of the coupling between flow and electrolysis. A reduced scale (4 cm x 4 cm x 1 m) transparent test section with multisegmented electrodes, electrochemical instrumentation and flow visualisation is presented as well as some of the more interesting results are discussed.

DERIVATION OF ELECTROMAGNETIC FIELD IN ANISOTROPIC MEDIA WITH A COMPLEX REPRESENTATION OF ELECTROMAGNETIC PARAMETERS

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The analitic solution of the problem deals with a derivation of electromagnetic field excited with a running current layer is obtained. This running current layer flows in the aerial medium parralel to anisotropic half-space where magnetic permeability and electrical conductivity of common aspect has axes displaced in according to coordinate axes choice on the angle of Φ. Electromagnetic field calculation in a conducting anisotropic medium is made using equations of macroscopic electrodynamics which by introduction of vector and scalar potential can be written equations system for vector and scalar potential determination. We choose scalar potential value by the way that equation with vector potential on current direction does not contain components of another directions.

We divide into two parts a problem of electromagnetic field determination in anisotropic medium with a complex representation of electromagnetic field parameters, which is caused by time alternating and X axis periodic currents $I_z exp j(\lambda_x x - wt)$, flowing in the aerial medium along the line parallel to Z axis. At the beginning we determine a value of Z component Fourie transformation from the system of equations at boundary conditions and regularity at infinity conditions. Taking into consideration determination of Z component of Fourier transformation of vector potential, we determinate a value of vector potentials A_x, A_y. This fact gives an opportunity to obtain the picture of electric and magnetic field distribution for many cases in practice (ferrites, electrical-sheet media and so on), not only for such representation but for more simple cases of electric conductivity and magnetic permittivity distribution. For example, for gyrotropic media, for media with diagonal representations of electrical conductivity and magnetic permeability with equal or different tensor terms.

REVIEW OF TURBULENCE STUDIES AT MHD CENTER OF THE BEN-GURION UNIVERSITY

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Turbulence in highly electro-conductive liquid flows undergoes most essential changes regarding its spatial and temporal characteristics, when exposed to an external magnetic field. The appearance of induced electrical currents causing additional Joule dissipation of energy and electromagnetic body forces resulting from the interaction of these currents with the magnetic field have to lead to quasi-two-dimensional turbulence. Spatial turbulent momentum transfer is suppressed and, as a result, the flow seems to be laminar as to frictional energy losses. However, velocity fluctuations are in no way decreasing. On the opposite, these fluctuations are growing manifold. Large-scale strongly anisotropic turbulent structures are prevailing. The three-dimensional turbulence energy cascade towards smaller eddies is suppressed, and instead an inverse energy transfer towards larger scales is apparently set on. All exposed above is convincingly demostrated by profound changes in energy spectra, as well as by strong enhancement of heat- and mass-transfer.

The above described trends and a variety of related phenomena have been intensively investigated over the last two decades in the Center for MHD Studies of Ben-Gurion University in Israel. The present paper gives a brief overview of the results obtained in a channel mercury flow under transverse magnetic field. A physical picture is outlined, and important applications are discussed. From the view-point of prospective engineering applications, these results are most relevant to the technology of liquid metal blankets of thermonuclear fusion reactors and, probably, also to different metallurgical devices. Another field of applications is related to the discovery of a profound physical analogy between anisotropic MHD turbulence and atmospheric and oceanic turbulence dominated by density stratification and Coriolis forces. This analogy permits convenient and relatively easy simulation of large-scale geophysical phenomena by small-scale laboratory experiments in liquid metal MHD flows.

ANISOTROPIC MHD AND ATMOSPHERIC TURBULENCE SPECTRAL SCALING

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MHD turbulence studies have revealed anisotropic quasi-two-dimensional properties of its characteristics. Efforts to simulate anisotropic geophysical turbulence, in particular, atmospheric one, by MHD laboratory turbulence were undertaken. Numerous observations of geophysical turbulence revealed spectral characteristics which do not fall within the frames of a two-dimensional model.

Different MHD turbulence modes were identified in our experiments carried out in a honeycomb generated turbulent flow of mercury in a channel under transverse magnetic field. Various modes of turbulence intensity and spectra depend on the interaction parameter $N = \sigma B^2 L/\rho U$. At low $N < 0.2$, turbulence intensity is decreased when N grows, and velocity spectra have a scaling range with the exponent close to -5/3. At $N \cong 1$ turbulence intensity grows significantly, and spectral exponent value jumps to -7/3. Atmospheric synoptic turbulence observations obtained at long distances by aircraft flights also revealed spectra having exponents close to those mentioned for MHD turbulence.

The similarity of the behavior of quasi-two-dimensional turbulence generated by various constraint factors, such as stratification, rotation, magnetic field action on a conductive liquid flow, is apparently caused by the turbulence helical properties. Generation of helical vortex structures is possible in continuous media under anisotropic or non-uniform conditions. In particular, this was obtained in the atmosphere under stratification and rotation conditions, as well as at the interaction of a stationary flow with helical turbulence. We obtain that the helicity $H = \langle(\mathbf{U}\ \mathrm{rot}\ \mathbf{U})\rangle$ of MHD turbulent flow is non-zero, because velocity fluctuations along the magnetic field and normal to it behave quite differently, having anisotropy correlation characteristics of the velocity field. In case of high helicity transfer rate $\eta \equiv dH/dt$, stationary velocity spectrum $E(k) = \eta^{2/3} k^{-7/3} f(kL_\eta)$ was valid, where $L_\eta = \varepsilon/\eta$, and ε is energy dissipation rate. If $k >> 1/L_\eta$, Kolmogorov's (-5/3) spectrum was obtained, while if $k << 1/L_\eta$, - spectrum defined by helicity: $E(k) \sim \eta^{2/3} k^{-7/3}$. Helicity transfer rate was estimated using ε and L_η for the observed spectra.

STABILISATION OF THIN LIQUID METAL JETS BY MAGNETIC FIELD

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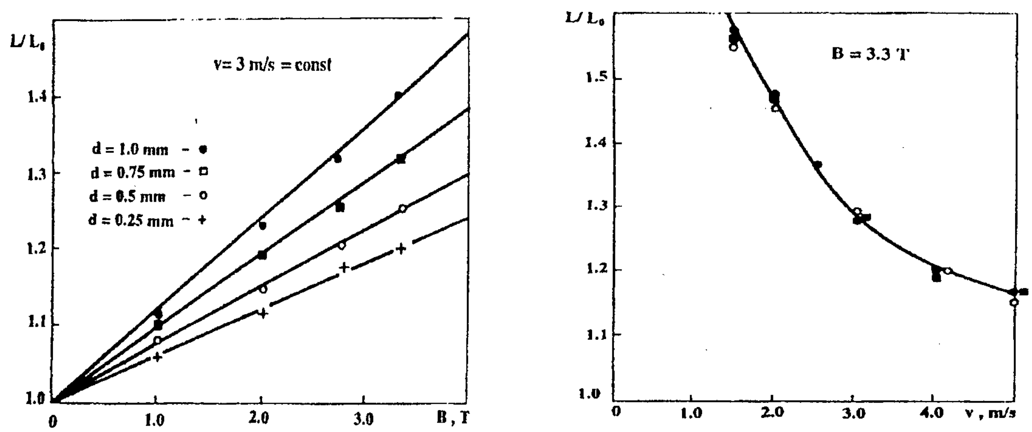
Free falling liquid jet disintegrates into droplets due to the well-known Rayleigh instability. It is known from classical papers of Chandrasekhar and Lenert, that this instability can be delayed by magnetic field, applied to the body of the jet. Earlier Riga experiments with eutectic alloy *In-Ga-Sn* issuing from cylindrical nozzles with diameter in the range of 1.5*mm*...2.5*mm* showed, that magnetic field stabilising effects are more expressed when perpendicular magnetic field is applied to the jet forming nozzle. These investigations were centred at demonstration of feasibility to create in strong magnetic fields the liquid metal shields, nontransparent to heat and particles fluxes. To extend the frame of potential applications to the small (0.01*mm*...0.1*mm*) diameter range, nondimensional rules are of great importance. Modelling experiments on mercury were carried out covering the range of cylindrical nozzle diameter d = 1.0; 0.75; 0.5 and 0.25*mm* and velocities V up to 5 *m/s* in transverse magnetic field varying up to 3.5*T* created in a small gap using permendure concentrators. Results presented in Fig. proved the concept, that defining nondimensional



criteria describing the relative length L/L_0 of continuous part of jet are: Weber number W, Reynolds number Re, Hartman number Ha. For investigated diameters the continuous part of jet L (measured by electrical contact) increases proportionally to the velocity and magnetic field strength, but decreases rapidly with nozzle diameter decreasing. The absolute length of continuous part of jet L_0 without magnetic field repeats with good accuracy the well-known dependence on We with a constant coefficient of "stability": $L_0 = 3.6d(We)^{1/2}$. The relative growth at the presence of field can in first approximation be characterised by a dependence on Ha/Re: $L/L_0 = 1 + k(Ha/Re)$. This corresponds to MHD concepts about damping of turbulence in channels resulting in jet stabilisation. For all investigated nozzle diameters the ratio of nozzle length and its diameter l/d was kept equal to 10. The k depending on nozzle diameter is $k = 133(d)^{1/2}$, where d is expressed in *mm*. And finally, the following empirical expression (basing on experimental results with mercury jets) have been derived:

$$L = 3.6d(We)^{1/2}[1+133(d)^{1/2}(Ha/Re)].$$

ELLIPSOIDAL BUBBLE GROWTH IN THE SUPERHEATED LIQUID METAL IN THE PRESENCE OF A MAGNETIC FIELD

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The problem of bubble growth in a superheated liquid metal in the presence of a uniform magnetic field is examined under the assumption of an ellipsoidal shape. A set of equations for bubble growth rates in the field direction and perpendicular to it, is derived. Different approximations have been used for the velocity field, induced in the surrounding liquid metal by bubble growth. Solution is found numerically and compared with analytical solutions describing asymptotic growth regimes at large times.

The influence of magnetic field is shown to result in a bubble shape elongated in the field direction. Asymptotically bubble grows linearly with time in the field direction and as a square root of time perpendicular to it. The growth constant in the field direction has maximum in its dependence on magnetic field, whereas growth constant perpendicular to the field direction decreases monotonically by increasing field.

In contrast to the case of bubble growth without magnetic field, where the grow is initially surface tension controlled, then inertia and finally heat transfer controlled, in the presence of magnetic field surface tension forces are important not only for early stages of growth but even for large times and bubble growth asymptotically is always surface tension controlled, but heat transfer controlled growth regime could be missing.

The relation between bubble growth characteristics and boiling Nusselt number ratio with and without magnetic field is discussed.

GLOBAL STABILITY OF EULER FLOWS PRODUCED BY MAGNETIC RELAXATION

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This paper is concerned with the stability of steady, inviscid flows with closed streamlines.Specifically, we examine the relationship between Arnol'd's variational approach to stability, Moffatt's magnetic relaxation technique, and a more recent relaxation procedure developed by Vallis et al. We start with two-dimensional (x, y) flows. Here we show that Moffatt's relaxation procedure will, under a wide range of circumstances, produce Euler flows which are stable. We also show that there is a close relationship between Hamilton's principle and magnetic relaxation. Next, we examine poloidal flows. Here we find that, by and large, our planar results also hold true for axisymmetric flows. In particular, magnetic relaxation once again provides stable Euler flows. Finally, we consider swirling, recirculating flows. It transpires that the introduction of swirl has a profound effect on stability. In particular, the flows produced by magnetic relaxation are no longer stable. Indeed, we show that all swirling, recirculating Euler flows are potentially unstable to the extent that they fail to satisfy Arnol'd's stability criterion.

INTERMITENCY IN SHELL MODELS OF 2D AND 3D MHD TURBULENCE

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The intermittency of energy cascade is studied in shell models of fully developed MHD turbulence, via the structure functions for both the velocity and magnetic fields and for the corresponding energy transfer rates. The models, written in complex variables, all conserve the fundamental symmetries of the MHD equations. They also conserve three quadratic quantities: the magnetic helicity (3D case) or the square of the potential vectorial (2D case), the total energy (kinetic plus magnetic) and the cross-helicity. The extended self-similarity [1] is used, to obtain a better estimate of the scaling exponents of structure functions at any order.

The shell models include only the local interactions and do not give the Iroshnikov-Kraichnan $k^{-3/2}$ law. The energy spectra for both 2D and 3D magnetohydrodynamics are close to $k^{-5/3}$ with a small correction ($E(k) \sim k^{-1.72\pm0.03}$).

The intermittency is studied within the frame of the hierachical intermittency model of turbulence of She and Lévêque [2], developped in the context of 3D hydrodynamic turbulence, discussed further by Dubrulle [3]. The model is characterized by two main parameters, Δ and β, describing respectively the smallest dissipative scales and the degree of intermittency of the energy transfers. These parameters are measured in both cases. In 2D-MHD model $\Delta = 0.22 \pm 0.03$, in 3D-MHD the intermittency is stronger and $\Delta = 0.36 \pm 0.05$. The parameter β in both cases is close to the value observed in 3D-HD turbulence ($\beta = 2/3$).

The results of the simulations are compared with a similar study done for shell models of Navier-Stokes turbulence [4], the influence of nonlocal interactions is discussed.

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EFFECT OF CONSTANT MAGNETIC FIELD ON THE FLOW DRIVEN BY A ROTATING MAGNETIC FIELD IN CYLINDRICAL VESSEL

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The paper presents a theoretical study of electrically conducting fluid flow driven by a rotating magnetic field (RMF) in a cylindrical vessel additionally subjected to a constant magnetic field (CMF). Rotating magnetic field is being used in various technological precesses for instance such as semiconductor crystal growth from the melt. The use of a rotating magnetic field alone provides limited possibilities of controlling of the enforced melt convection and creation of conditions the most favorable for the single crystal growth. A constant magnetic field imposed additionally to the rotating one is considered as a suitable tool to "improve" the hydrodynamic characteristics of the flow due to RMF. Upon common assumptions the problem under consideration becomes defined by the following dimensionless parameters: T - electrodynamic Taylor number specifying the characteristic magnitude of magnetic forcing due to RMF, Ha - Hartmann number defining the characteristic braking force due to CMF. We consider the flow regimes, which are still laminar, but already dominated by the inertial forces. The main feature of such flow regimes is a presence of the core region, where the magnetic forcing is balanced by the Coriolis like inertial force. The scaling analysis shows that a substantial effect of the CMF begins to take place, when the magnetic braking reaches the order of magnitude of inertial forces in the core of the flow. The required strength of CMF depends on both the magnitude of forcing due to RMF and particular electric properties of the end walls of the container. The corresponding Hartmann numbers are found to scale as $Ha \propto T^{1/3}$ and $Ha \propto T^{1/6}$ for case of insulating and conducting end walls, respectively. If the end-walls are insulating, then electromagnetic braking begins to dominate over inertial forces in both core region and boundary layer simultaneously at the same characteristic CMF strength. If the end walls are well electrically conducting, then the induced electric current passes the boundary layer along the axial CMF flux lines to enter the end-walls normally, what results in a negligible electromagnetic braking there. Thus, the inertial force still persists to dominate in the boundary layer, when it has already been outweighted by the electromagnetic braking in the core of the flow. As a result, the weak CMF scaling of flow characteristics is no more valid, but that of strong CMF is not yet reached. This range of the moderate Hartmann numbers has its own specific scaling of boundary layer thickness and meridional circulation rate. The scaling of the moderate Hartmann numbers persists up to $Ha \propto T^{1/4}$, where the inertial force in the boundary layer is outweighted by the magnetic forcing there. Predictions of the scaling analysis are found to fit well the results of numerical calculations. Besides that, numerical simulations show, that application of sufficiently strong CMF causes a considerable reduction of the spin-up time, and makes the spin-up itself to proceed more smoothly by damping numerous over- and under-shoots of rotation rate occuring during the spin-up. In general, application of CMF is found to stabilize the flow, so that the critical Taylor number T_c, at reaching of which an oscillating flow regime replaces the steady one, increases with the Hartmann number as $T_c(Ha)-T_c(0) \propto Ha^2$.

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COHERENT STRUCTURES IN A QUASI-TWO-DIMENSIONAL MHD-FLOW

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Coherent structures in two-dimensional flows of ideal fluids are studied using a recently developed statistical theory[1,2]. These final states of two-dimensional turbulence are evaluated as solutions of a multiconstrained variational problem of maximizing a Boltzmann mixing entropy for the microscopic vorticity distribution. The variational problem is solved numerically using an efficient iterarative algorithm[3]. The theory is applied to to the case of a box geometry. It is found that in dependence of the initially fixed conserved quantities monopoles or dipoles maximize the entropy. The results are compared both with novel experimental results of a freely decaying quasi-two-dimensional MHD-flow[4] and high resolution direct numerical simulations[5,6]. In order to model the dissipation in the Hartmann layer on the bottom of the experimental confinement the 2-D-Navier-Stokes-equation contains a linear friction term in addition to the molecular viscosity. The effect of the linear friction leads to an exponential damping of the fluid motion. Therefore a complete mixing is impossible if the caracteristic damping time is smaller than the necessary turbulent decaying time. Then the structure of the vorticity field appears to be frozen at a finite time and the final states of maximum entropy cannot be reached.

Furthermore the theory is extended to the so-called "balanced forcing case". Here a stationary forcing is applied to the 2-D flow which is balanced by a linear friction in such a way that the energy flux through the flow is stationary too. The results of the statistical theory are compared with laboratory simulations of Jupiter's Great Red Spot and direct numerical simulations.

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THE ACCELERATION OF CONDUCTING FLUID BY ROTATING MAGNETIC FIELD IN FINITE LENGTH VESSEL

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One – dimensional nonstationary quasi – laminar and turbulent flows of conducting fluid caused by two – dimensional rotating magnetic field with one pair of poles in cylindrical round finite length vessel are studied at negligible induced magnetic field with using "external friction" model. It is supposed that the side wall was made of dielectric and butt – end walls of conductor with conductivity equals to conductivity liquid.

The average velocity of this flow is described in cylindrical coordinates r, φ, z by the following dimensionless equation

$$\frac{Re_\omega}{2\pi}\frac{\partial \bar{v}_\varphi}{\partial \tau} = \Delta \bar{v}_\varphi - \beta^2 \bar{v}_\varphi + Ha_\partial^2 r, \tag{1}$$

where $Re_\omega = \omega R_0^2/\nu$, $\Delta = \partial^2/\partial r^2 + 1/r\partial/\partial r - 1/r^2 + 1/\delta_z^2 \partial^2/\partial z^2$, $\beta^2 = Ha_\partial^2 + \lambda_\varepsilon$, $\lambda_\varepsilon = C_\varepsilon (Re_\omega < \bar{\Omega} >)^{1-\varepsilon}/f(\delta_z)$, $\delta_z = Z_0/R_0$, Z_0 — half height of vessel, $C_\varepsilon = 0.0165 \cdot e^{11,6\varepsilon}$, $f(\delta_z) = exp\left[Ath\left(ln\delta_z/AC\right)\right]$, A = 11,23167, C = 0.98596, $< \bar{\Omega} >= \sqrt{< \bar{\Omega}_z >^2 + < \bar{\Omega}_r >^2}$, $< \bar{\Omega}_z >= \frac{1}{2}\int\limits_0^1\int\limits_0^1 |rot_z \vec{v}| r dr dz$, $< \bar{\Omega}_r >= \frac{1}{2}\int\limits_0^1\int\limits_0^1 |rot_r \vec{v}| r dr dz$.

Boundary and initial conditions are

$$\bar{v}_\varphi\Big|_{r=1} = 0, \quad \bar{v}_\varphi\Big|_{z=1} = 0, \quad \frac{\partial \bar{v}_\varphi}{\partial z}\Big|_{z=0} = 0, \quad v_{\varepsilon=2}\Big|_{\tau=0} = 0. \tag{2}$$

This problem is solved by Galerkin's method with series expansion

$$\bar{v}_\varphi = \sum_{k,n=1}^{\infty} v_{kn}(\tau) J_1(\alpha_k r) cos(\gamma_n z), \tag{3}$$

where α_k — roots of equation $J_1(\alpha_k) = 0$, $\gamma_n = (n - 1/2)\pi.$,

$$v_{kn} = \frac{4Ha_\partial^2}{\nu_{kn}^2}\frac{sin\gamma_n}{\alpha_k \gamma_n J_0(\alpha_k)}\left(e^{-P_{kn}\tau} - 1\right),$$

$$\nu_{kn}^2 = \alpha_k^2 + \beta^2 + \gamma_n^2/\delta_z^2, \quad P_{kn} = 2\pi\nu_{kn}^2/Re_\omega$$

$$< \Omega_z >= 4Ha_\partial^2 \sum_{k,n=1}^{\infty} \frac{sin^2\gamma_n \left|\int\limits_0^1 r J_0(\alpha_k r) dr\right|}{\alpha_k \gamma_n^2 J_0(\alpha_k)\nu_{kn}^2}\left|e^{-P_{kn}\tau} - 1\right|, \tag{4}$$

$$< \Omega_r >= \frac{4Ha_\partial^2}{\delta_z}\sum_{k=1}^{\infty} \frac{sin\gamma_n \left|\int\limits_0^1 sin\gamma_n z dz\right| \left|\int\limits_0^1 r J_1(\alpha_k r) dr\right|}{\alpha_k J_0(\alpha_k)\nu_{kn}^2}\left|e^{-P_{kn}\tau} - 1\right|. \tag{5}$$

Good agreement with experiments date has been obtained.

THE TURBULENT VISCOSITY IN "EXTERNAL FRICTION" MODEL

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The "external friction" approximation is a simple effective method of describing the average quasi – laminar and turbulent rotation flows which are caused by rotating magnetic field in cylindrical vessel.

The main idea of this method is the approximation of Reynolds stress tensor by the vector whose components are proportional to the average velocity.

In average azimuthal flow case

$$\frac{1}{r}\frac{\partial}{\partial r}(r\overline{u'v'}) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}(r\overline{v'^2}) + \frac{1}{\delta_z r}\frac{\partial}{\partial z}(r\overline{v'w'}) = \frac{\lambda_\varepsilon \bar{v}_\varphi}{Re_\omega} \quad (1)$$

where $\lambda_\varepsilon = C_\varepsilon(Re_\omega < \bar{\Omega} >)^{1-\varepsilon}/f(\delta_z)$, $Re_\omega = \omega R_0^2/\nu$, $< \bar{\Omega} >= \frac{1}{2}\left|\int\limits_0^1 rot_z \bar{v} r dr\right|$, ε — empirical parameter which is completely determines the flow pattern, $C_\varepsilon = 0.0165exp(11.6\varepsilon)$, $f(\delta_z) = exp[Ath(ln\delta_z/AC)]$, $\Lambda = 11.23167$, $C = 0.98596$.

Leaving in (1) only tangential components of Reynolds stresses and considering that in consequence with isotropy we have

$$\frac{1}{r}\frac{\partial}{\partial r}(r\overline{u'v'}) = \frac{1}{\delta_z r}\frac{\partial}{\partial z}(r\overline{v'w'}) \quad (2)$$

than we obtain

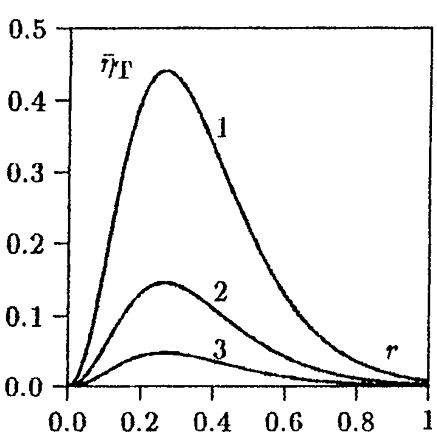
$$\frac{Re_\omega}{r}\frac{\partial}{\partial r}(r\overline{u'v'}) = \frac{\lambda_\varepsilon \bar{v}_\varphi}{1 + 1/\delta_z}. \quad (3)$$

The Reynolds stress τ_{R} is

$$\tau_{\mathrm{R}} = Re_\omega \overline{u'v'} = \frac{\lambda_\varepsilon \int r\bar{v}_\varphi dr}{(1 + 1/\delta_z)r}. \quad (4)$$

and dimensionless turbulent viscosity is

$$\bar{\eta}_{\mathrm{T}} = \frac{\lambda_\varepsilon \int\limits_0^r r\bar{v}_\varphi dr}{(1 + 1/\delta_z) r^2 \frac{\partial}{\partial r}(\bar{v}_\varphi/r)}. \quad (5)$$



The turbulent viscosity profile with the conditions $\delta_z \to \infty$, $Ha_\partial = 10$, $Re_\omega = 10^6$ is shown in the picture where 1 — $\varepsilon = 0$, 2 — $\varepsilon = 0.5$, 3 — $\varepsilon = 1$.

The behavior of turbulent viscosity near the curved curvilinear wall is the same as the known distribution which is close to the planar wall.

TURBULENT COUETTE FLOW IN ROTATING MAGNETIC FIELD

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The turbulent and quasi – laminar Couette MHD – flow are of great interest in connection with MHD – bearings and centrifugal casting of pipe MHD – systems engineering. The Couette flow of viscous incompressible conducting fluid which is induced by rotation of interface or external walls and magnetic field $\vec{B} = \vec{B}_0 expi(\omega t - \varphi)$ at negligible induced magnetic field is studied with using the "external friction" model.

The average velocity of azimuthal flow is described in cylindrical coordinates r, φ, z, which rotate with angular velocity $\Omega_0 = (\Omega_1 + \Omega_2)$, by following dimensionless equation

$$\frac{d^2\bar{v}_\varepsilon}{dr^2} + \frac{1}{r}\frac{d\bar{v}_\varepsilon}{dr} - \frac{\bar{v}_\varepsilon}{r^2} - \beta^2\bar{v}_\varepsilon = -Ha_\partial^2 r \tag{1}$$

with boundary conditions

$$\bar{v}_\varepsilon\Big|_{r=\delta} = (\bar{\Omega}_1 - \bar{\Omega}_0)\delta, \bar{v}_\varepsilon\Big|_{r=1} = (\bar{\Omega}_2 - \bar{\Omega}_0). \tag{2}$$

where $\bar{v}_\varepsilon = V_\varepsilon/\omega R_2$, $\beta^2 = \lambda_\varepsilon + Ha_\partial^2$, $Re = \omega R_2/\nu$, $\lambda_\varepsilon = C_\varepsilon(Re < \bar{\Omega} >)^{1-\varepsilon}/f(\delta_z)$, $\delta = R_1/R_2$, $\delta_z = Z_0/R_2$, $Ha_\partial = B_0 R_2\sqrt{\sigma/\nu}$, $< \bar{\Omega} >= |\int_\delta^1 rot_z\bar{v}_\varepsilon r dr|/2(1-\delta)$.

Solution of problem (1) – (2) is

$$\bar{v}_\varepsilon = C_1 I_1(\beta r) + C_2 K_1(\beta r) + Ha_\partial^2 r/\beta^2, \tag{3}$$

where

$$C_1 = \frac{G_1 K_1(\beta) - G_2 K_1(\beta\delta)}{I_1(\beta\delta)K_1(\beta) - I_1(\beta)K_1(\beta\delta)},\ C_2 = \frac{G_2 I_1(\beta\delta) - G_1 I_1(\beta)}{I_1(\beta\delta)K_1(\beta) - I_1(\beta)K_1(\beta\delta)},$$
$$G_1 = (\bar{\Omega}_1 - \bar{\Omega}_0 - Ha_\partial^2/\beta^2)\delta,\ G_2 = \bar{\Omega}_2 - \bar{\Omega}_0 - Ha_\partial^2/\beta^2.$$

In fixed coordinate system

$$\bar{v}_\varphi = \bar{v}_\varepsilon + \bar{\Omega}_0 r. \tag{4}$$

The average by volume vorticity of velocity $\bar{v}_\varepsilon$ is

$$< \bar{\Omega} >= \left|\frac{\bar{\Omega}_2 - \bar{\Omega}_1\delta^2}{2(1-\delta)} - \frac{\Omega_0(1+\delta)}{2} - \frac{Ha_\partial^2(1+\delta)}{2\beta^2}\right| + \frac{Ha_\partial^2(1+\delta)}{2\beta^2}. \tag{5}$$

The viscous shear on interface and external envelopes is

$$\bar{\tau} = \left|\frac{\partial\bar{v}_\varphi}{\partial r} - \frac{v_\varphi}{r}\right| + \frac{\lambda_\varepsilon}{1 + 1/\delta_z}\int r\bar{v}_\varphi dr\Big|_{r=\delta,1} \tag{6}$$

The problem of stability laminar and quasi - laminar flows with using power considerations and Rayleigh number analog for MHD - flow has been also studied.

MULTICHANNELS MEASUREMENTS IN TWO-DIMENSIONAL JET TYPE MHD FLOW

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The goal of the proposed experiment is to study the turbulent evolution of a twodimensional jet flow in a circular channel. The fluid comes to narrow layer rotation by means of electrical force. To create a circular liquid metal flow with two opposite vorticity strips an electrical forces' drive has been used.

The annular channel consists of a main cylindrical container and inner cylinder in the central part of container. Two circular electrodes for electric current supplying are placed at the bottom of container. An interaction of an imposed on the system external axial magnetic field with a radial electric current creates an azimuthal volume force in the fluid. By means of this force the fluid comes to rotation in narrow layer between electrodes.

The form of the flow is nearly two dimensional. When a forcing parameter exceeds the critical value, the flow undergoes an instability. The shear layer instability produces a chain of vortices traveling in azimuthal direction. The basic vortex street looses its monoperiodic character at increasing values of parameters and new degrees of freedom appear in the flow. The flow comes to regime of chaos. While well understood in the framework of dynamical systems transition to temporal chaos, generation of spatio-temporal complexity in continuous system is a subject of intensive investigation. The novelty of this experiment consists in the measurement technique that is a multichannel measurement technique for simultaneous measurements of few flow characteristics in a single point or at different spatial locations. Also, the novelty consists in a new idea for local vorticity measurements.

Eight potential probes were used for measurements. The probes were mounted into device along the circumference of an annular channel between forcing electrodes. The later permit to perform the measurements of spatial scales in the flow. Two probes for potential and vorticity simultaneous measurements were located on upper lid of the device. They were located in a point of vorticity maximum above the external power supplying electrode. The output signals of these probes were being considered as two independent variable quantities in a dynamical process of vortex interaction.

In this report we present measurements series of these characteristics for growing values of electric driving current.

LOCAL PROPERTIES OF A Hg/N_2 BUBBLY FLOW INJECTED BY A SINGLE ORIFICE IN A LONGITUDINAL MAGNETIC FIELD

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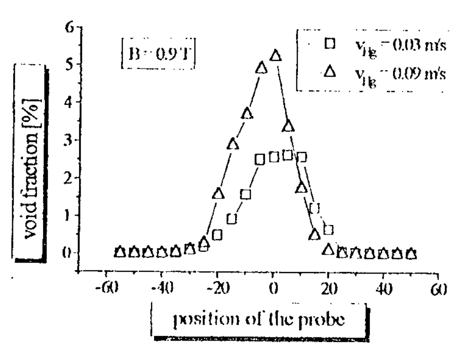
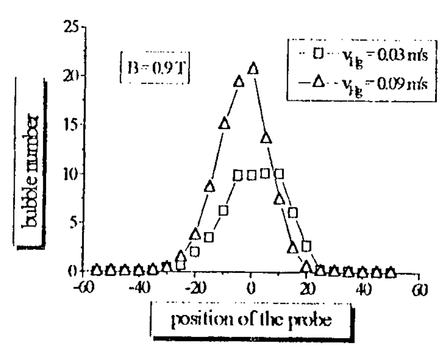
For the design of gravity type LMMHD generators the knowledge about the momentum transfer from the rising gas to the liquid metal is essentially, because of the decisive role of the mean slip ratio ($S = v_{gas}/v_{liquid}$) on the overall generator efficiency. Thus, it does make sense to look for methods to reduce the slip ratio. It is known from former investigations that the drag force of a spherical body will be increased by a magnetic field. Numerical calculations by means of a simple, one-dimensional model for MHD bubbly flows based on corresponding empirical closure laws revealed the following behaviour:

- In the case of a transverse magnetic field the slip ratio decreases first with increasing field strength (due to the enhancement of the bubble drag coefficient ~ B), however, after passing a minimum S rises again (due to the braking effect on the liquid metal flow ~ B^2)
- The absence of the braking effect in the case of a longitudinal magnetic field results in a monotonous decrease of the slip ratio with increasing field intensity and in a corresponding increase of the mean void fraction, respectively.

In order to confirm this fact experimentally, local measurements in a mercury/nitrogen two-phase flow were performed at the vertical mercury loop with solenoid (diameter: 0.2 m, length: 2 m, B: up to 1 T) and electromagnetic pump (pressure: $5 \cdot 10^5$ N/m^2, flow rate: $5 \cdot 10^{-3}$ m^3/s) located in the Institute of Physics. A special probe system is available allowing to move local probes for measurements of the void fraction and the liquid velocity along a line over the cross section (diameter: 0.16 m) of the vertical tube. The gas was injected through a single orifice in the centre. Values of the local void fraction were determined by single wire resistivity probes. We will present results regarding the mean velocity profiles in the test section, the mean slip ratio for different values of the magnetic field and the mercury flow rate. Profiles of the local void fraction and of the local bubble number will be shown depending on parameters like the magnetic field strength, the gaseous or the liquid flow rate (see figures).





TRANSPORT PROCESSES IN TWO-DIMENSIONAL SHEAR TURBULENT FLOWS UNDER LARGE TRANSVERSE MAGNETIC FIELD

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Behaviour of the Reynolds' stresses and turbulent energy production in liquid metal free shear plane-parallel and closed circular flows were experimentally investigated. In both cases, the shear flows without longitudinal pressure gradient were created by electromagnetic force $\mathbf{j} \times \mathbf{B}$ using external electric current and applied magnetic field B up to 1.45 T.

In the plane-parallel flow, the sign of the Reynolds' stress $\tau = -\rho <u'v'>$ was changed to the axial plane of symmetry, and the turbulent energy production $P = -\rho <u'v'> \partial U/\partial y$ was positive in whole flow cross-section. Extreme of these values were located in zones on velocity gradient at the points of maximum velocity pulsation.

In the circular flow, the Reynolds' stress τ distribution was similar to previous case. The energy production $P = -\rho <u'v'> r\, \partial/\partial r\, (U/r)$ was also positive with the exception of axial region in which $P < 0$. The sign change of energy production in this region is apparently connected with a curvature of the flow and energy transfer from perturbations into the flow. Similar change of sign, but in all flow cross-section at transverse strong magnetic field, was also received in 2d free shear flow behind slit located in the beginning of a channel (A. Votcish and Yu. Kolesnikov, 1976).

Both the flows are characterized by high level of turbulent pulsation intensity (16-25% relatively to maximum averaged velocity). It has been received by spatial correlation measurements that the turbulence originated is two-dimensional. Cross-sectional distributions of averaged and pulsation velocity profiles along the flows are similar. There is a correspondence between the energy production and dissipative losses. It was also received common a stability criterion in which the relationship between sizes of flow was taken into account. Analysis of intensity and direction of momentum transport processes in the flows' cross-section have been performed using the measurements of longitudinal and transversal velocity pulsation and asymmetry co-efficient of turbulent perturbations.

The research described in this publication was made possible in part by Grants No. LBJ000 and No. LIS100 from the International Science Foundation.

ON THE STABILITY OF CIRCULAR COUETTE FLOW IN A NONUNIFORM MAGNETIC FIELD

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Recently, the stability of fluid flows driven by different factors [1]-[3] has received much attention. The study of rotating flows of a conducting fluid in a magnetic field has drawn the interest of many applications (like improving the performance of rotating components in modern machinery) and different astrophysical applications. Several papers have investigated the stability of circular Couette flow between two rotating cylinders in a uniform magnetic field (see, for example, [4], [5]). In practice, however, one often deals with nonuniform magnetic fields.

An example of a stability problem for a Couette flow in a radial magnetic field of the form

$$\mathbf{H}(r) = \frac{H_0}{r}\mathbf{e}_r$$

is given in [6]. The study in [6] was restricted to the case of axisymmetric disturbances and small Hartmann numbers. Moreover, only the case where the inner cylinder is rotating and the outer one is at rest was considered.

In the present paper, we generalize the results of [6] to the case of asymmetric disturbances. Moreover, a larger range of Hartmann numbers and two rotating cylinders are considered.

A pseudospectral collocation method based on Chebyshev polynomials is used for the numerical study of the stability boundary. The eigenvalue problem is solved by the LZ-algorithm. Numerical results are presented for both asymmetric and axisymmetric disturbances and for the case of co-rotating and counter-rotating cylinders. It is found that the critical Taylor numbers increase as the Hartmann number grows. Moreover, a nonuniform magnetic field leads to a considerable increase of stability boundary as compared with a uniform magnetic field [5].

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BOUNDARY LAYERS FORMATION IN CASE OF FREE AND NEAR THE WALL FAN JETS AT THE ELECTRICALLY INDUCED VORTICAL FLOWS

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The analogs of free and near the wall fan jets (Loitsyansky's problem), which are inducing by the going throw the fluid electrical current at the own magnetic field, is considered basing on the theory of similar axisymmetrical boundary layer. The flow inducing physical mechanism and the corresponding electrical current flow function are described. The 4th order differential equation for the flow in the boundary layer region is reduced to the 1st order differential equation. The method for determining the integration constants is given. The matter is, what there are not enough the boundary conditions to determine all of these constants exactly. That is why is necessary to use the flow out of the boundary layer. This flow is viscous and non potential. Solving the equation for external flow asymptotically and using what the solution for the boundary layer aspire to the solution for the external flow at the infinity, is possible to determine all of the necessary constants. The friction on the solid wall is given for near the wall jet analytically; the value for the radial component of velocity at the plane of symmetry is given for the free jet. The numerically computed profiles for axial and radial components of velocity are given for the both problems. The pictures of flow are given in the both cases also.

The research described in this publication was made possible in part by Grant No. LFE 000 from the International Science Foundation.

METHOD FOR ELECTROMAGNETIC FIELD CALCULATION IN MHD PROBLEMS WITH NON-INDUCTIVE APPROXIMATION

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In cases considering motion of electrically conducting fluids under the effect of an alternating magnetic field, it is rather difficult to determine skin-effect. So, the so-called non-inductive approximation is used. This approximation is applied when the field of currents $\mathbf{H}^1$ induced in the fluid is small comparing to the idle running field $\mathbf{H}^0$of the inductor ($\mathbf{H}^1 << \mathbf{H}^0$), and it can be neglected. Hence, $\mathbf{H}^0$ can be taken as the resulting magnetic field. The distribution of this field is easy to calculate using, for example, the Biot–Savart law. But electric field $\mathbf{E}$ and current $\mathbf{j}$ remain uncalculated because $\mathbf{H}^0$ has been found in void, where $\sigma = 0$ ($\mathbf{rotH} = \mathbf{j} = \sigma\mathrm{E}$).

The following two methods are proposed to overcome the difficulties.

1. The technique of loop currents. Any real inductor of an alternating magnetic field is a set of loops through which currents go (their amplitude, phases and even frequencies may differ). If these loops are large, they can be divided into smaller ones (even infinitely small) in such a way that the total sum of current in the smaller loops will be equal to that of the large one. Each elementary loop can be considered as a magnetic dipole moment ($\mathbf{M} = \mathrm{I}\mathbf{Sn}$, where S is the loop square, $\mathbf{n}$ is the unity vector in the normal direction). It induces vector potential $\mathbf{A} = \mu_0/4\pi(\mathbf{M}\mathrm{x}\mathbf{R})/\mathrm{R}^3$, where R is the vector directed from the loop to the observation point. Further, it is not difficult to define $\mathbf{B}$ and $\mathbf{E}$: $\mathbf{B} = \mathbf{rotA}$, $\mathbf{E} = -\partial\mathbf{A}/\partial t = -i\omega\mathbf{A}$. These equations are valid for the case, when there are no ferromagnetic and electrically conducting bodies in the vicinity of the "loop – point-of-observation" system. The advantage of the technique discussed is that there arise no infinity problems.

With regard to a flat one-sided inductor of a travelling field the above order is presented in [1] in details, but in [2] it is used for calculation of a rotating field of the inductor with account for its forebody parts.

2. The technique of moving coordinates. It can be used when travelling or rotating magnetic fields are employed. The technique runs as follows: if steady magnetic field $\mathbf{B}$ is described in some system of coordinates, then there is no electric fields connected with $\mathbf{B}$. But in a coordinate system moving relatively to the discussed one with velocity $\mathbf{v}$, there will appear an additional electric field $\mathbf{E} = \mathbf{v}\mathrm{x}\mathbf{B}$. If B is considered as the idle running field and $\mathbf{v}$ is the field motion velocity, then $\mathbf{E}$, correspondingly, is the electric field intensity in the given inductor. If consider the Maxwell general equations assuming corresponding systems of coordinates, then we get $E_y/B_x = E_\varphi/B_r = \pm\omega/\alpha$ and $E_z/B_r = \pm\omega r/p$. The field components B_z, B_y and B_r do not appear in the case discussed because it has been assumed that $\mathbf{v}$ has only one v_z–component or, correspondingly, v_φ–component.

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THE MHD-FLOW PROBLEMS CALCULATION BY METHOD OF FUNDAMENTAL SOLUTIONS

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In this paper two MHD-flow problems corresponded to the perturbed Hartman flow are presented.

First we consider the problem of computing of the velocity and induction current of a viscous, conducting, incompressible fluid flowing between two parallel nonconducting plates with a thin nonconducting rib placed within the flow region in the presence of a transversal magnetic field (see fig.1).

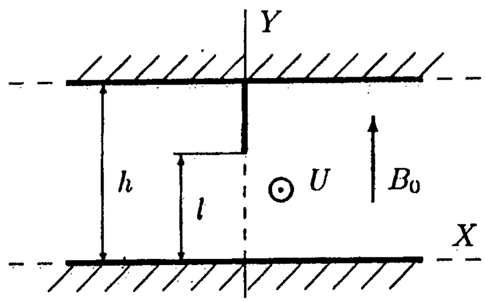

Figure 1: Flow domain

We used a new technique which is based on the method of fundamental solutions (MFS) [1] and the method of local singular expansions (MLSE) [2] combination.

Governing equations:

$$\Delta U + Ha\frac{\partial B}{\partial y} = 1, \quad \Delta B + Ha\frac{\partial U}{\partial y} = 0,$$

where $U(x,y)$ is the velocity, $B(x,y)$ - the induction of magnetic field, Ha –the Hartman number.

By standard transformation

$$W_{\pm}(x,y) = U(x,y) \pm B(x,y), \quad W_{\pm}(x,y) = W_{\pm}^{0}(y) + e^{\mp yHa/2}\Psi_{\pm}(x,y)$$

where $W_{\pm}^{0}(y)$ corresponds to nonperturbed Hartman flow, we obtain:

$$\Delta\Psi - \left(\frac{Ha}{2}\right)^2 \Psi = 0$$

both for Ψ_+ and Ψ_-.

Boundary conditions:

$$\Psi_{\pm}(x,h) = \Psi_{\pm}(x,0) = 0, \quad 0 \le x < \infty,$$

$$\frac{\partial \Psi_{\pm}}{\partial x}(0,y) = 0, \quad 0 \le y \le l,$$

$$\Psi_{\pm}(0,y) = -e^{\pm yHa/2}W_{\pm}^{0}(y), \quad l < y \le h.$$

In the suggested method the different forms of solutions in the singular point neighbourhood and in the external domain have been used. The internal solution form is

$$\Psi_{\pm}(\rho,\theta) = V^0_{\pm}(\rho,\theta) + \sum_{k=1}^{\infty} A_{\pm,k} I_{k-1/2}(\rho Ha/2)\sin((k-1/2)\theta)$$

where (ρ,θ) are polar coordinates, $A_{\pm,k}$ – unknown coefficients, $I_{k-1/2}$ – modified Bessel functions, $V^0_{\pm}(\rho,\theta)$ – any partial solutions.

Outside the singular point neighbourhood the solution can be represented as a linear combination of exact solutions for a channel without a perturbing rib. The coefficients in both expansions are obtained by matching them across any interface around the singular point.

Also we consider a problem of the Hartman flow perturbation by a conducting strip which is placed on the nonconducting wall of the channel.

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THE TURBULENT MHD-FLOW OF CONDUCTIVE FLUID IN SCREW COIL PIPE WITH CIRCULAR CROSS SECTION

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The coil pipes are widely used in hydraulic systems and the MHD – phenomenas in them are being of great interest.

The turbulent flow of viscous incompressible fluid in the screw channel with circular cross section and walls, the conductivity of which assume close to liquid, that is in constant radial magnetic field $B_r = B_0\rho_0/\rho$ is studied with using the "external friction" model.

This flow at the negligible induced magnetic field is described in cylindrical coordinates r, φ, z which are connected with starting screw coordinates ρ, θ, ζ by relations $\rho = 1 + r cos\varphi$, $\zeta = r sin\varphi$ following dimensionless equations

$$L\bar{v}_\theta - \beta^2\bar{v}_\theta = \delta_\theta\frac{\partial\bar{p}}{\partial\theta}, \quad \frac{\partial p}{\partial r}cos\varphi - \frac{1}{r}\frac{\partial p}{\partial\varphi}sin\varphi = Re\text{æ}^2 v_\theta^2 cos^2\alpha, \quad \frac{\partial p}{\partial r}sin\varphi + \frac{1}{r}\frac{\partial p}{\partial\varphi}cos\varphi = 0, \tag{1}$$

$$\bar{v}_\theta\Big|_{r=r_0} = 0, \quad \bar{v}_\theta\Big|_{r=0} < \infty, \quad \bar{v}_\theta(\varphi) = \bar{v}_\theta(\varphi + 2\pi), \tag{2}$$

where

$$L = \Delta + T, \quad T = cos\varphi\frac{\partial}{\partial r} - \frac{sin\varphi}{r}\frac{\partial}{\partial\varphi}, \quad \Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2},$$

$$\text{æ} = \frac{\rho_0}{r_0,} \quad Re = \frac{V_0 r_0}{\nu}, \quad V_0 = \frac{\Delta p_0 r_0}{\eta}, \quad \beta^2 = Ha^2 + \lambda_\varepsilon - cos^2\alpha(2 - 3cos^2\alpha)$$

Representing the operator L as $L = \Delta + \varepsilon T$ and assuming that ε is a small parameter we search for the solution of problem (1) – (2) in form

$$\bar{v}_\theta = \sum_{k=0}^{\infty}\varepsilon^{k+1}v_k, \quad \bar{p} = \sum_{k=0}^{\infty}\varepsilon^{k+1}p_k = \theta\sum_{k=0}^{\infty}\varepsilon^{k+1}Q_k. \tag{3}$$

If $\varepsilon \to 1$ and if we have the convergent series, this transformations give good approximation of fluid velocity and pressure. With the first approximation accuracy of the parts we have

$$\bar{v}_\theta = v_0 + cos\varphi\sum_{m=1}^{\infty}\frac{\mathcal{F}_m J_1(\lambda_m r/r_0)}{\lambda_m^2 + \beta^2}, \tag{4}$$

where

$$\mathcal{F}_m = \frac{2\lambda_m I_1(\beta r_0)\delta_\theta Q_0}{[(\beta r_0)^2 + \lambda_m^2]J_0(\lambda_m)\beta I_0(\beta r_0)}, \quad Q_0 = \frac{\partial p_0}{\partial\theta},$$

$\delta_\theta = (2\pi cos\alpha)^{-1}$, λ_m — roots of equation $J_1(\lambda_m) = 0$.

The viscous shear on the walls of the channel is

$$\bar{\tau} = \left|\frac{\partial\bar{v}_\theta}{\partial r} - \frac{v_\theta}{r}\right| + \frac{\lambda_\varepsilon}{1 + 2\pi cos\alpha}\int r\bar{v}_\varepsilon dr d\varphi\Big|_{r=r_0} \tag{5}$$

and the hydrodynamic friction coefficient is

$$\lambda = 2\bar{\tau}/Re < \bar{v}_\varepsilon >^2 \tag{6}$$

The results of calculations with using this model are well agreed with those of the experiments.

STABILITY OF A LIQUID SHEET OF METAL SUBMITTED TO A PARALLEL OR TRANSVERSE MAGNETIC FIELD

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In previous works, the possibility of using an electromagnetic device in the process of gas atomization for liquid metal powder production has been discussed (see 1 for example). The basic principle consists in driving into rotation the liquid column of metal by using an electric device which delivers a rotating magnetic field. At the tube outlet, this has the effect of transforming the liquid metal flow into an axisymetric conical sheet which can be easily disrupted into fine droplets by the action of a parallel co-streaming gas flow.

The stable, ie. unperturbed solution for the sheet profile has been already discussed in ref. 2 as a function of the governing non-dimensional parameters which are the Weber, Froude and Rossby numbers. From the latter study, it become possible to foresee the location of the region where the external gas flow will interact with the film and will destabilize the interface by Kelvin-Helmholtz instabilities generation (denotes as the interaction zone on fig.1). Nevertheless, due to geometrical constraints, it can be necessary to design the location of this region at a distance which is sufficiently far from the nozzle outlet. In other words, one has to avoid that natural instabilities of the film will lead to its fragmentation before to reach the gas stream. Using a magnetic field can be a good technique for preventing, or postponing, the appearance of this natural instability.

We present the linear stability study of a liquid sheet, having a velocity V, in the presence of a parallel or transverse magnetic field and subjected to parallel gas flows on its both sides, with possibly different velocities V_1 and V_2. The use of two-dimensional cartesian coordinates will be discussed. The results, which can be looked at as an MHD generalisation of the pure hydrodynamic situation described in ref.3 for the simpler case $V_1 = V_2$, will be also compared to the results presented in ref.4 and concerning the effect of a transverse field on the stabilization of an interface subjected to Rayleigh-Taylor waves.

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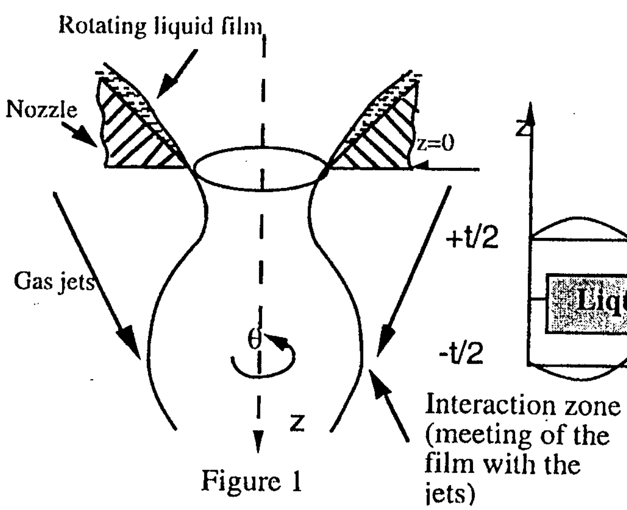

Figure 1

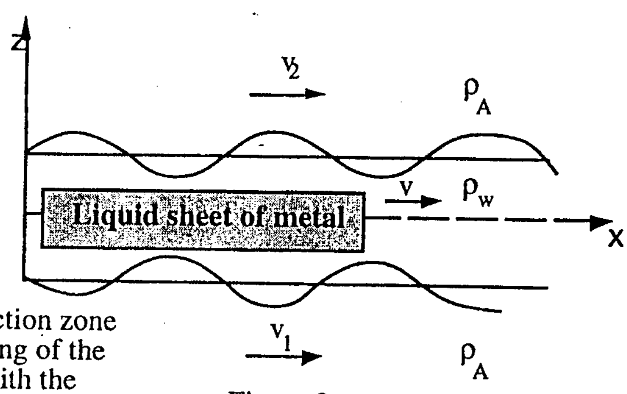

Figure 2

THE SOLITARY WAVE ON A POISEUILLE STREAM IN CROSSED ELECTRIC AND MAGNETIC FIELDS

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As it was shown recently [1], the sech squared solitary-wave amplitude on a stream with constant vorticity enormously exceeds the limit amplitude of the irrotational solitary wave due to a closed eddy beneath the wave crest [2]. Different solitary waves may be induced by the method [3] based on the MHD effects in weakly conducting media. In the present work a generalization of the method is considered theoretically that enables to obtain the solitary wave on the incompressible perfect stream with linear vorticity.

We extend the Rayleigh's formulation of the weakly dispersive solitary-wave problem when the wave is fast compared with the upstream Poiseuille flow. The weak nonlinearity and nearly critical regimes are not assumed. The interaction of the external nonuniform horizontal magnetic field **B** perpendicular to the side walls of the channel with the current **j** flowing along the wave-propagation direction leads to the electromagnetic force having the horizontal $rot(\mathbf{j} \times \mathbf{B})$ linear with respect to the vertical co-ordinate. Induced electric current and magnetic field are supposed small compared with the external ones. An analytical solution is given for the finite-amplitude solitary wave under some restrictions on the channel width and the gap shape when the problem can be splitted into the 2D electrical, magnetic and fluid problems. In the absence of the MHD force, the solution reduces to Lamb's irrotational wave and, for enough small nonlinearity and nearly critical flows, to Benjamin's rotational wave.

The results show that there is a specific range of the Froude number in which a closed eddy appears on the solitary-wave crest. Both the first critical value of the Froude number F_1 providing the existence of the rotational solitary wave and the second critical value F_2 yielding the closed eddy are calculated. In the second supercritical regime a curved region of constant vorticity appears inside the eddy as the flow deflects closer to the bottom due to inertial forces. Dependencies of F_1 and F_2 on parameters of the problem, the flow structure in the motionless frame and the frame moving with the wave are also discussed.

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TURBULENT FLOW OF CONDUCTING FLUID IN HOMOPOLAR DEVICE

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The device of the type of homopolar is used in physics of plasm and in technological processes of metallurgy and chemistry.

Turbulent flow of viscous incompressible fluid which is caused in the homopolar device by the action of radial current density $j = j_0 R_2/r$ and the uniform axial magnetic field B_z at negligible induced magnetic field with using "external friction" model has been studied.

The average velocity of rotation flow is described in the cylindrical coordinates r, φ, z by the following dimensionless equation

$$\frac{d^2\bar{v}_\varepsilon}{dr^2} + \frac{1}{r}\frac{d\bar{v}_\varepsilon}{dr} - \frac{\bar{v}_\varepsilon}{r^2} - \beta^2\bar{v}_\varepsilon = -Ha^2/r \tag{1}$$

with boundary conditions

$$\bar{v}_\varepsilon\Big|_{r=\delta,1} = 0, \tag{2}$$

where $\bar{v}_\varepsilon = V_\varepsilon/V_0$, $V_0 = E_0/B_z$, $\beta^2 = \lambda_\varepsilon + Ha^2$, $Re = V_0 R_2/\nu$, $\lambda_\varepsilon = C(Re < \bar{\Omega} >)^{1-\varepsilon}/f(\delta_z)$, $\delta = R_1/R_2$, R_1, R_2 — radiuses of interface and external walls of vessel, $\delta_z = Z_0/R_2$.

The solution of problem (1) – (2) is

$$\bar{v}_\varepsilon = C_1 I_1(\beta r) + C_2 K_1(\beta r) + \frac{Ha^2}{\beta^2 r}, \tag{3}$$

where

$$C_1 = \frac{Ha^2[K_1(\beta) - \delta K_1(\beta\delta)]}{\beta^2\delta[I_1(\beta)K_1(\beta\delta) - I_1(\beta\delta)K_1(\beta)]}, \quad C_2 = \frac{Ha^2[\delta I_1(\beta\delta) - I_1(\beta)]}{\beta^2\delta[I_1(\beta)K_1(\beta\delta) - I_1(\beta\delta)K_1(\beta)]}$$

The average by volume vorticity of velocity $< \bar{\Omega} >= Ha^2/\beta^2(1-\delta)$ or

$$< \bar{\Omega} >^{2-\varepsilon} + Q_\varepsilon < \bar{\Omega} > - Q_\varepsilon/(1-\delta) = 0, \tag{4}$$

where $Q_\varepsilon = [Ha^2 f(\delta_z)/C_\varepsilon Re^{1-\varepsilon}]^n$, $n = 1$ for integer ε and $n = 2$ for other.

The viscous shear expression on interface and external walls of vessel

$$\bar{\tau} = \left|\frac{d\bar{v}_\varepsilon}{dr} - \frac{\bar{v}_\varepsilon}{r}\right| + \frac{\lambda_\varepsilon}{1 + 1/\delta_z}\int r\bar{v}_\varepsilon dr\Big|_{r=\delta,1} \tag{5}$$

and hydrodynamic friction coefficient

$$\lambda_r = \frac{2\bar{\tau}}{Re < \bar{v} >^2} \tag{6}$$

have been obtained.

The problem of stability of laminar and quasi - laminar flows with using power considerations has been also discussed.

THEORY OF AXISYMMETRICAL BOUNDARY LAYER IN ORDINARY AND MAGNETO HYDRODYNAMICS

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Proposed theory unifies all known in the theory of boundary layer flows and also permits to predict new flow types, which may be considered in the theory both in hydrodynamics and in MHD. The application of rot operator to Navie-Stokes equation allows to exclude the pressure, but axial symmetry permits to reduce the task to the definition of four function: y - hydrodynamic stream function, y_1 , y_2 - electrical and magnetic stream function and y_3 - stream function of vorticity of azimuthal velocity. In all four defining equation Happel-Brener operator

$$E^2 = \frac{\partial^2}{\partial z^2} + r\frac{\partial}{\partial r}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial r}$$

presents and further analysis is carried out using the properties of this operator. If the main role the first term plays, then, by example, function y is determined in the form

$$y = Ar^a f(Bzr^b)\ . \qquad (1)$$

In this case there are restriction on values of a and b : $a \geq 1$, $b \geq -1$. Such boundary layer are considered as first type layers. As an example of them Loitsyansky's fan jet and solutions of Karman class can be mentioned. If the main role in the E^2 the second term plays, then y is determined in the form

$$y = Az^a f(Brz^b)\ . \qquad (2)$$

with restriction $a \geq 1$, $b \geq -1$. Such boundary layer are considered as second type layers. As an example of them the Schlichting's round jet can be considered. There exist also cross considerations, when , by example, the first term in the E^2 plays the main role, but vorticity stream function is in form (2). Such, not considered previously in hydrodynamics boundary layers are considered as boundary layers of third and fourth types. For all these cases the forms of other functions have been presented. The forms of equations for non induction and electrodynamic approximation have been derived. The possible external meridional electric current , which do not disturb the similarity of solutions, have been considered. The solution of specific boundary layers tasks have presented.

The research described in this publication was made possible in part by Grant No. LFE 000 from the International Science Foundation.

VARIATIONAL METHOD FOR CALCULATION OF MHD FLOWS IN RECTANGULAR CHANNELS OF VARIABLE CROSS SECTIONS IN STRONG MAGNETIC FIELDS (Ha>>1)

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A steady flow of a viscous conducting fluid in the channel $|x| < \infty$, $|y| \leq a$, $|z| \leq h(1 + \varepsilon \cos \alpha x)$ with nonconducting walls is considered in the presence of a strong uniform magnetic field $\mathbf{B} = B_0 \mathbf{z}$ in inertialess approximation $(\mathrm{N} \cdot \mathrm{Ha}^{-3/2} >> 1)$.

At the first stage, the initial problem is reduced to a 2D one by averaging with respect to the channel height under an assumption that the velocity components v_x and v_y in an arbitrary cross section x have the Hartmann profile along the z axis. Distributions of the averaged quantities are further described by hydrodynamic, $\chi(x,y)$, and electric, $\psi(x,y)$, stream functions.

A periodic, with respect to x, solution of the obtained system of equations is constructed by the Galerkin-Kantorovich variational method. If the choice of basic functions describing the dependences of χ, ψ and pressure $\langle p \rangle$ on the coordinate x has been restricted by the first harmonic, the distributions of hydrodynamic and electric fields over the channel width are determined from the system of four second-order ordinary differential equations with constant coefficients.

The proposed method allows to obtain in a highly simple analytic solution describing the flow structure in the channel and to determine, with an accuracy fully sufficient for practical purposes, the pressure gradient averaged along the channel length versus Ha and geometric characteristics of the channel as well.

EFFECT OF EXTERNAL ELECTRIC FIELD ON METALS

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Electrodynamics issues from the fact that external electrostatic field does not penetrate inside ideal conductor. For non-uniform conductor in which moreover there is a temperature gradient, just such is a metal being crystallized, that is not so. In view of non-uniformity of a conductor the electric charges are redistributed in it. This is equivalently to the presence of internal volumetrical charge of the density on the creating electric field

$$\rho = -\varepsilon_o \vec{E}\frac{\nabla \sigma}{\sigma} \tag{1}$$

where $\vec{E} = \vec{E}(\vec{r},\tau)$ is the electric field intensity;

$\sigma = \sigma(\vec{r})$ is the electroconductivity of metal.

Generalization of Ohm's law for irregular heated metal with non-equilibrium distribution of the components was obtained by Onzagera's method:

$$\vec{j} = \sigma\cdot\vec{E} - \sigma\cdot\alpha\cdot\nabla T - \sum_{k=1}^{P}\sum_{i=1}^{N} L_{ki}\cdot\nabla\left[\frac{\mu_i}{T}\right] \tag{2}$$

where $$\sigma = -\sum_{i,k=1}^{P} M_{ki} q_i; \quad \sigma\cdot\alpha = -T^2\sum_{k=1}^{P} L_{k\alpha}; \tag{3}$$

M_{ki}, L_{ki}, $L_{k\alpha}$ – phenomenological Onzagera's coefficient;

M_i – chemical potential of i-component; T – temperature.

Formula (2) within the accuracy of the latter item coincides with formula (26.2) of the work [1,p.44] where diffusion phenomena which are described by this latter item were not taken into account. It follows from the formula (2) that in the non-uniform isotropic electroconductive medium electric current may arise also when absent of electric field inside the metal (E_{int}=0). If the metal under consideration is not switched on into closed chain then electric current in such a system is absent (j=0) and distribution of charges will be stationary. In this case

$$E_{int} = \alpha\cdot\nabla T + \frac{1}{\sigma}\sum_{k=1}^{P}\sum_{i=1}^{N} L_{ki}\cdot\nabla\left[\frac{\mu_i}{T}\right] \tag{4}$$

Thus arising in the metal internal electric field penetrates into environment and can be observed there. Interaction of external electric field with internal one may result in alteration of the latter and consequently to have an influence upon the processes induced forvation of this field, that is, upon the processes of displacement of heat and mass, what is marked in the experimental works.

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DISSIPATION-RATE MODELLING IN ANISOTROPIC TURBULENT FLOWS

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The Kolmogorov's local-isotropy hypothesis, which states that at sufficiently high Reynolds numbers the small-scale structures of turbulent motions are independent of large-scale structures and the mean deformation rate, has been used in most approaches to understanding turbulence.

The resent experimental studies have shown that turbulence does not remain locally isotropic either in the presence of gravity, magnetic, centrifugal forces nor in the presence of strong strain fields. However, there are no equations for determination of tensor dissipation-rate for locally anisotropic turbulent flows.

In the work reported here the closure models for all terms of the exact equation for tensor and scalar dissipation-rate were investigated including mixed production, production by mean velocity gradient, gradient production, turbulent production, turbulent transport, pressure transport, viscous diffusion and dissipation.

Among the most successful and popular turbulence models are the various second-order closure schemes. These models attempt to express the physical properties of turbulence in a universal mathematical form. All models contain a number of adjustable numerical coefficients. In this work a method of tensor approximation and other methods were used to determine a general form of the expressions for terms of a dissipation-rate equation.

Basically three methods may be employed to determine the empirical coefficients in closure approximations: indirect method, direct comparison of the closure models to experimental data for terms of exact equation and direct comparison to numerical simulation data.

In the indirect method the adequacy of the models is judged by computing a flow with the model and by comparing the predicted mean velocity and Reynolds stresses with experimental data. Unfortunately, the results of the comparison cannot be interpreted unambiguously. The terms in the exact equation for tensor dissipation-rate cannot be measured and, therefore, information on these terms can only be obtained from direct numerical simulation (DNS) data.

In recent years numerical simulations of turbulent flows have become an important research tool in studying the basic physics of turbulence. Extensive efforts has been devoted to the calculation of a turbulent channel flow. In the computations of Mansour N.N., Kim J, Moin P. (1987 J. Fluid Mech., 194, 15-44) the grid resolution was sufficiently fine to resolve the essential turbulent scales.

The database generated by such a simulation is of a considerable value for the design and testing of turbulence closure models. On the base of DNS data the system of empirical coefficient has been determined. The closure model for dissipation-rate was used for determination of expressions for tensor dissipation- rate in a general form for three-dimensional flows. These expressions may be used for computations of locally anisotropic turbulent flows such as flows in presence of gravity, magnetic and inertial forces.

NUMERICAL INVESTIGATION OF ELECTROCONVENCTION HEAT TRANSFER FOR CYLINDER-PLANE ELECTRODE SYSTEM

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An electroconvection and heat transfer by electrohydrodynamic flows in liquid dielectrics are considered. The study is made for an poorly conducting liquid between cylindrical and plane electrodes on the basis of dissociation-injection conductivity model [1]. The injection of ions X^- is assumed on the cathode according to reaction $X + e^- \Rightarrow X^-$ where X is the molecule of electronoacceptor. In the liquid volume there are two impurity ions A^+, B^- which are formed due to dissociation reaction $A^+B^- \to A^+ + B^-$ and ions X^-, A^+ recombinate according to reaction $X^- + A^+ \to X + A$.

Taking into account these assumptions the basic equations of stationary EHD flow are [1]

$$\rho(V\nabla)V = -\nabla p + \eta\Delta V + qE, \qquad \mathrm{div}\ V = 0$$

$$\mathrm{div}\ \varepsilon E = 4\pi q\ , \quad E = -\nabla\Phi\ , \quad q = e(n_1 - n_2 - n_3)$$

$$\mathrm{div}\ [(-1)^{j-1} b n_j E_j + n V_j] = \Sigma_j\ , \quad j = 1, 2, 3$$

$$\Sigma_1 = \Sigma_2 - \alpha_1 n_1 n_3\ , \quad \Sigma_2 = k_d N - \alpha_p n_1 n_2\ , \quad \Sigma_3 = -\alpha_1 n_1 n_3\ .$$

Here V is the velocity, η is the dynamics viscosity, ρ is the mass density, E is the electrical strength, ε is the dielectric permittivity, Φ is the electrical potential, q is the space charge density; n_j, b_j are the volume concentration and mobility of ions A^+ ($j=1$), B^- ($j=2$), X^- ($j=3$); N is the volume concentration of the ion pairs A^+B^-; k_d is the dissociation rate and α_p, α_1 are the recombination constants of ions A^+, B^- and A^+, X^- accordingly; e is the charge of proton.

Numerical investigations has been made for the case of linear injection law on the cathode, i.e. $n_c(E) = \eta_c E$, where η_c is the injection coefficient. Heat transfer was determined by the equation

$$\rho c_p V\ \nabla T = \lambda\Delta T.$$

It has been assumed that the temperature of electrodes is constant. Succesive over-relaxation method has been used for solving stream function and electrical potential equations. The vorticity and concentration equations are solved by fractional-step method. Polar coordinates are used for the region around cylindri-

cal cathode. Numerical calculations are made for cathode with diameter d_e=0.05-0.4 sm and distance between electrodes d_0=0.5 sm. It has been shown that heat transfer is fulfiled through temperature boundary layers forming on the electrodes.

Average Nusselt number determined as $Nu_a = \int_0^{2\pi} \frac{\partial T}{\partial r} r d\varphi$ depends on $RE^{0.5}$, where $RE = b_2 U/\nu$, U- is applied voltage. For the case of low injection and small mobility of injecton ions $b_3 \ll b_2, b_1$ bypolar layer with positive and negative ions are formed near cylindrical cathode and the heat flux decreasing corresponds to RE increasing. When RE has reached some critical point ($RE \sim 0.2$) bypolar layer is destroyed and heat flux is enhanced with RE increasing. The calculations have shown good agreement between theory and experiments [2].

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Numerical Methods

COMPUTATION OF FLUID FLOW AND FREE SURFACE OF LIQUID METAL DUE TO THE ELECTROMAGNETIC FORCES

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In this paper a method of numerical computation of the fluid flow field coupled with the electromagnetic field is discribed. The electromagnetic forces are calculated by a programpackage named "PROMETHEUS" which was developped by the department of electrical heat at the Technical University of Ilmenau. The electromagnetic force density is the base to calculate the field of fluid flow and the free surface of the melting metal considering internal flow effects with the commercial programpackage "FIDAP". The mainproblem of this work is the connection of the programpackages "PROMETHEUS" and "FIDAP" due to the incompatibities of the both programs.

The mathematical model of the electromagnetic and fluidmechanic fields and the method of the Finite Elements are discribed. After that some results of the simulation of the liquid metal flow and the free surface are presented in some examples at medium-frequency. The difficulty problem of the simulation of the free surface is to reach the convergence and the present results show a good stabilization for the free surface.

THE NUMERICAL SIMULATION METHODS DEVELOPMENT FOR THREE-DIMENSIONAL ELECTROMAGNETIC FIELDS MODELLING

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A problem of multi - dimensional electromagnetic fields simulation is of great importance for many areas of human activity. An existence of subdomains with sharply nonhomogeneous features in simulation region creates some additional complications. The process of macrobodies electrodynamical acceleration provides us for a great set of problems and tasks connected with modelling of electromagnetic fields.

The algorithms for simulation one - , two - and three - dimensional in space phenomena basing on finite - difference method have been constructed. These algorithms are constructed on the base of mathematical model in terms of vector potential that enables us to calculate fields in whole accelerator homogeneously. The big set of calculations has been made by means of such algorithms. Partially the different dependencies of acceleration effectiveness on process parameters were studied.

Three - dimensional model of cylindrical railgun with moving solid armature has been studied. Its construction demands for composition of materials with different features that include different magnetic permeability. The constructive elements comprise rails, conducting armature, entire containment different types of dielectrics. Developed mathematical model enables us to simulate different fields through entire railgun homogeneously. Our model is based on the real launcher from M.Holland et al., "AJAA Pap.", 1992, N 0085.

Electromagnetic fields, initiated by flowing current, dissipate to the containment, therefore the energy partly loses. On the contrary the containment allows to vary inductance gradient value and current form in circuit. We have applied numerical experiment method for investigation of influence of containment physical characteristics up the launch process.

The set of calculations has been made. We altered geometry and material of the containment. Inductance gradient, armature velocity, maximal temperature value and distribution of electromagnetic fields were the main output data. Obtained results actually allow to define the containment materials for better railgun characteristics. It is really possible to change form of current curve in whole railgun circuit.

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NUMERICAL SIMULATION OF FLUID FLOW IN CYLINDRICAL CONTAINERS INDUCED BY A ROTATING MAGNETIC FIELD

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In the last decades there has been considerable interest shown in the rotation of liquid metals in cylindrical containers by electromagnetic fields. Transverse rotating magnetic fields are used for stirring and mixing of liquid metals and electrically conducting melts in general. One major application is continuous steel casting. Besides there is a growing interest in the use of rotating magnetic fields in crystal growth experiments. It is expected to influence the fluid flow in semiconductor melts and somehow improve the crystal quality[1].
Therefore a thorough understanding of the flow in circular cylindrical containers induced by rotating magnetic fields is necessary. Numerical simulations provide a way to analyze the flow for different magnetic Reynolds numbers Re_m, Hartmann numbers Ha and various aspect ratios h/d in case of a finite cylinder.
The commercial software $FIDAP^{TM}$ [2], which is based on the Method of Finite Elements, was used to perform the simulations. To check its accuracy, numerical results are compared with the analytical solution of a well known problem of axisymmetric flow resulting from a transverse rotating magnetic field in an infinite cylinder [3]. In the low frequency limit the Lorentz force results as a linear function of the radius (1), neglecting time dependent, irrotational components. We state the analytical solution of the axisymmetric laminar Navier-Stokes equations for the azimuthal velocity component v_φ (2) as a polynomial function:

$$F_\varphi(r) = \frac{1}{2}\rho\left(\frac{U}{R}\right)^2 r \quad , \quad v_\varphi(r) = \frac{U^2 r}{16\nu R^2}\left(R^2 - r^2\right) \qquad (1),(2)$$

$$U = BR(\sigma\omega/\rho)^{1/2}$$

R -radius, ρ -density, σ -electrical conductivity, ω -angular velocity, ν -kinematic viscosity
The results obtained with $FIDAP^{TM}$ concerning the velocity field (fig.1a), pressure and streamline function agree well. Fig.1b shows the corresponding axisymmetric flow on a circular horizontal cut.
In addition, results on secondary flow and instabilities for different aspect ratios $0 \leq h/d \leq 4$ and magnetic fields $B \leq 10$ mT in finite cylinders will be presented.

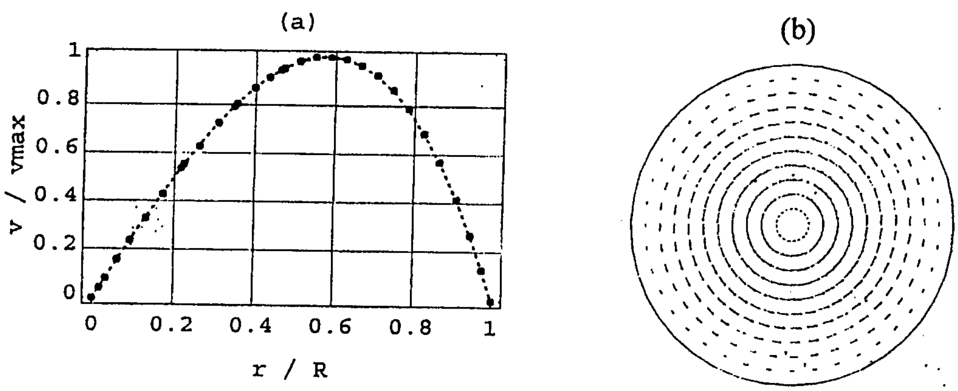

Fig.1: (a) Radial velocity profile for the azimuthal component v_φ. Analytic (dashed line) and numerical (circles) results. (b) Velocity field v on a circular horizontal cut.

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DECAY OF MESH TURBULENCE IN A LONGITUDINAL MAGNETIC FIELD: NUMERICAL EXPERIMENT

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The three-parameter differential turbulent model (V.G. Lushchik, A.A. Pavel'ev, A.E. Yakubenko (1978)) in which transport equations are written for turbulent energy, shear stresses and transverse integral scale of turbulence was extended to conducting fluid flows in a longitudinal magnetic field.

Additional terms connected with the turbulence properties taking into account the Joule dissipation and the anisotropy of turbulence in a magnetic field, their form and structure being determined from dimensional considerations and an analysis of the transport equations for the components of the turbulent energy were introduced into the transport equations. The constant entering into the model was determined so that with respect to the drag coefficient for developed flow in a tube and the numerical results agreed with the experimental data (F.W. Fraim, W.H. Heiser (1968), E.Yu. Krasil'nikov, V.G. Lushchik, V. S. Nikolaenko, I.G. Panevin (1971)). The dependence of the lower critical Reynolds number on the Hartman number thus obtained corresponds to experiment.

For the case of uniform mesh turbulence with zero and constant shear instead of the equation for turbulent energy the equations for longitudinal and transverse components of velocity fluctuations are used.

In the case of very strong magnetic field, the analytical solutions for decay of mesh turbulence with zero shear in isotropic and approximations have been received.

For intermediate values of magnetic field, the numerical solution have been also received. The comparision of calculation results with the known experimental data (A. Alemany, R. Moreau, P.L. Sulem, U. Frisch (1979), and V.A. Voronchihin, L.G. Genin, V.B. Levin, V.G. Sviridov (1984-1987)) concerning the decay of mesh turbulence in a longitudinal magnetic field have been carried out.

PREDICTION OF FLOW VELOCITIES IN LINEAR STIRRING IN CONTINUOUS CASTING OF BLOOMS

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Flow velocities in linear stirring of continuously cast blooms were calculated using a commercial computational fluid dynamics package. To take the electromagnetic forces into account user subroutines were developed and added to the code. The model was verified by comparing the results of the force calculation to the results found in the literature. Flow velocities were calculated varying the casting speed, solid shell thickness, magnetic field strength and the frequency of the stirrer power.

The goal of the study was to find the effect of the stirring parameters on the flow field in the remaining melt within the solidifying bloom. The results show that velocities in the melt are strongly dependent on the thickness of the solidified shell. Therefore, the stirring parameters need to be adjusted according to the casting parameters to be able to get sufficient stirring effect on the liquid core at all times. A sufficient flow is strong enough to give the benefits of the stirring such as avoiding the formation of pores and segregation but not too strong to cause the harmful white band formation.

The shell thickness and the width of the mushy zone was defined using a mathematical model developed to calculate the temperature distribution in the continuously cast strand. The location of the solidification front was also defined experimentally from sulphur prints. With the help of the results of the computations and experimental data from industrial trials proper placement and driving parameters of the stirrer were found.

The assumptions in the model and its limitations are discussed. The plans for future development of the model and possibilities to include dynamic stirrer control to a process control system of the casting machine are discussed.

MATHEMATICAL MODELLING OF THE SOLIDIFICATION OF LIQUID TIN WITH ELECTROMAGNETIC STIRRING

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It is well known that during alloy solidification, convection currents close to the solidification front have an influence on the structure of dentrites, the local solute concentration, the pattern of solid segregation, and eventually the microstructure of the casting and hence its mechanical properties. Controlled stirring of the melt in continuous casting or in ingot solidification is thought to have a beneficial effect. Free convection currents occur naturally due to temperature differences in the melt and for any given setup, their strength is a function of the degree of superheat present. A more controlled forced convection current can be induced using electromagnetic stirring.

The authors have applied their generic Control-Volume based MHD method[1,2] to the problem of tin solidification in an annular crucible with a water-cooled inner wall and a resistance heated outer one, for both free and forced convection situations and for various degrees of superheat. This problem was studied experimentally by Vives and Perry[3] who obtained temperature measurements, front positions and maps of electromagnetic body force for a range of superheat values. The results of the mathematical model are compared critically against the experimental ones, in order to validate the model and also to demonstrate the usefulness of the technique as a predictive tool and a design aid. Good correlation is obtained with the experiment.

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APPLICATION OF COMBINED METHOD TO NUMERICAL SIMULATION OF ELECTROMAGNETIC AND HYDRODYNAMIC PROCESSES IN MOLTEN METAL

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Combined method submitted in this work is qualified as a method for analysis of processes in magnetohydrodynamics devices, which are characterized by absence of ferromagnetic core and by existence of external open region containing inductor. For example, system for magneto-pulse processing and treatment of crystallizing metal and system for formation of free surface of liquid metal belong to those MHD-devices.

The combined method contains finite-difference method for analysis of processes in the melt and boundary element method for its use in space out of melt region. Significant merit of this approach in comparison with, for instance, method of volume integral equations is a simple account of nonlinear characteristics of conductor, namely, electrical conductivity and magnetic permeability as functions of a temperature. Besides, such approach gives a possibility to consider electromagnetic, thermal and hydrodynamic processes on one and the same space grid. Finite-difference method and method of boundary elements are the best and optimal methods for analysis of the processes in the conductor and in its external open region containing inductor, respectively. That is why, the combined method, which unites algorithmically these two numerical methods in the one common execution program, possesses computational effectiveness.

The combined method has been used to investigate electromagnetic and hydrodynamic processes in molten metal, which is under the action of pulse magnetic field. The investigation has been carried out for the following two cases: pulse magnetic field is created by flat inductor located over free surface of the melt (i.e. meniscus) and by solenoid, which causes pinch forces. Problem solving has been divided into two stage. In the first place, it is solution of electromagnetic problem for penetration of pulse magnetic field in depth of liquid metal as well as determination of electromagnetic force distribution for different time moment. And, in the second place, it is determination of liquid metal motion according to distribution of the electromagnetic forces.

In this work, optimal value of pulse length (when the molten metal accelerates to maximal velocity in time of force action of electromagnetic field) has been determined. The influence of pulse length and inductor disposition on liquid metal motion has been examined. Existence of optimal position of the inductor, provided melt velocity reaches its the largest value, has been shown.

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THE NUMERICAL SIMULATION METHODS DEVELOPMENT FOR MULTIDIMENSIONAL ELECTROMAGNETIC FIELDS MODELLING IN APPLICATION TO ACCELERATION PROCESS OF SOLID CONDUCTING ARMATURES

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The numerical experiment is important tool for investigation of complicated physical phenomena such as processes flowing at electrodynamical acceleration of plasma and solid armatures. Authors have developed and realized as software the set of numerical algorithms for numerical simulation of such processes.

The model based on finite - element method for investigation of processes in domains with boundaries of arbitrary shape has been developed. This model has feature of full conservativeness that is it describes energetic relations as original differential model. The numerical model is quasimonotone and doesn't permit unphysical oscillations. We developed different variants of such model, partially, nonlinear model with limited artificial viscosity.

The model was applied to investigation of processes in electrodynamical accelerator of railgun type at launching of solid conducting armatures. In this case the algorithm is based on model in terms of magnetic field strength and is realized for two - dimensional case. A problem of existence of continuous metal contact between armature and rail in railgun electromagnetic launchers was investigated by means of it. The main aim of this investigation is the establishment of conditions at which it is possible to extend the range of armature velocities with continuous metal contact. It enables to improve the acceleration effectiveness and to increase railgun bore - life.

The used physical and mathematical acceleration model itself included description of fields diffusion into rail and armature, armature acceleration, mutual friction and heating of conductors, heat conductivity, melting and evaporation of armature. We denote "critical" velocity the velocity at which the temperature reaches boiling one. The model enables to simulate acceleration process of armature with arbitrary shape.

We have applied numerical experiment method for investigation. The critical velocity altitudes were stated in dependency on shape and material of armature, geometry characteristics, preacceleration, rail material, layer structure in armature or rail and mutual friction of conductors. The developed model has been tested on comparison with results of real shots. In particular it has been shown a limitation of common idea about "critical" velocity. In reality a melting and evaporation of solid armature may occur at zero velocity when a construction has angle points with angles more π.

NONINDUCTANCE APPOXIMATION OF ELECTRICALLY INDUCED VORTICAL FLOW IN THE SHEET OF VORTICITY

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A problem of electrically induced vortical flow (EVF) theory[1] is discussed aimed at computation of flow between two parallel planes caused by interaction of the electric current with its self-magnetic field. The solution of this problem can be brought to the solution of ordinary differential equations system due to singularities of electric current spreading ($\psi_e = Ar^2z$).

To solve this problem in automodelling setting of it various methods were tried. Nonstationary approach to estimation of univariate flow with analogs of vorticity and stream function is considered proper and natural here. Using irregular mesh with the number of mesh points equal to 351 and with distance between planes z_0 minimum mesh space near the wall was equal to $5 \cdot 10^{-7} z_0$. This makes the main advantage of the avtomodelling setting. Strong univariance limitation is in the fact that vortexes are infinity closed.

In addition to the study of induced currents influences on EVFs with high values of parameters the study of properties and differences of automodelling and space solutions is also the matter of interest. With the same electric function conditioned by its axially symmetric leakage on the isolated surface, by solution of Navier-Stokes equations system according to [2], EVF was in cylinder container of relative radius $R_0 = 1$ and height $z_0 = 0.25$.

With high values of parameter S [1] (in the range of 10^8 ..10^{14}) in electrodynamic approximation automodelling problem has a multiplicity of solutions. With small, subcritical value of mesh space in time Δt the solution is nonstationary. Secondary vortex occurs periodically, the value of which depends upon parameter S. Initial, immovable state of fluid is the unstable point from which a multiplicity of stationary two-vortexes flows can be obtained depending upon Δt. Increase of Δt provides for transfer from periodic solution to stationary solutions with axcess of secondary vortex.

Induced currents influence on EVF was studied with values of Batchelor number β in the range of from 0 to 1. Minimum β value becomes smaller with the growth of parameter S when flow is not only suppressed but its structural change begins.

In calculations of EVF in cylinder container the mesh with minimum mesh space relative to r and z near boundary equal to 0.001 was used. Therefore it was impossible to obtain the multiplicity of solutions analogue to automodelling one. In which case definite univariance frames are also absent. In response to number β encrease the flow reacts in structural change with practically unchanged maximum velocity value.

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Metallurgical Applications

TURBULENCE AND LOW-FREQUENCY OSCILLATIONS IN THE THOROIDAL ELECTROMAGNETICALLY INDUCED VORTICAL MELT FLOW

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The investigations of the turbulent electrically induced vortical flow in the cylindrical domain have both theoretical (the oscillations are generated in the volume) and practical importance. The latter is determined by the essential dependence of the technological processes (for instance, mass transfer and homogenization of the melt) and lifetime of the furnaces on the character of the flow. The flow patterns can be characterized by the developed turbulence and the presence of two or more thoroides of averaged circulation for the typical Reynolds numbers above 105. Small penetration depth of the electromagnetic (EM) field ($\delta << 1$) determines the absence of the EM vortical forces and the EM field itself in almost all volume of the melt.

A PC controlled experimental device operating with Wood metal was constructed for the investigations of the averaged flow and the oscillations of the velocity and temperature. Efficient cooling system allowed long continuous measurements [1]. The temperature was measured by the thermopairs while the EM sounds for simultaneous recording of two velocity components was employed in the flow studies. Measurements were performed for the different fill levels of the device in the range of non-dimensional frequencies $\tilde{\omega}$ 50 to 500.

Experiments show that in the core of the flow the anisotropic turbulence field may be assumed as axisymmetric. The energy of the axial component of oscillations essentially differs from the approximately equal energies of azimuthal and radial oscillations. The radial oscillations decay faster in the vicinity of the side wall, while from the remaining azimuthal and axial components the latter predominates. The essentially non-homogenous distribution of the turbulent kinetic energy (TKE) in the flow region is found with the maximum values in the vicinity of the side wall between the thoroidal vortices of the averaged flow. The averaged velocity and the TKE indicate characteristic frequency dependence at the fixed power: $v \sim \tilde{\omega}^{-1/2}$ and $v \sim \tilde{\omega}^{-1}$, respectively.

The Fourier analysis of the measured signal indicates low frequency velocity pulsations with the characteristic periods 1 to 20 s and different energy and period in the different flow regions. For instance in the zone between the thoroidal vortices in the vicinity of side wall the axial velocity pulsations with 10 s period predominate. The intensity of the low frequency oscillations is lower in the other regions with predominate oscillations of period of few seconds.

The model of the development of the inertial waves in a rotating fluid with low viscosity confirms the existence of low frequency oscillations. It allows also estimations of the TKE values and the pulsation periods. Another pulsations in such devices (surface waves, self-oscillations) are considered, too. Averaged flow and the parameters of turbulence can be modelized by the 2D k-ε model in the isotropic approach. The model has to be enhanced by inclusion of the generation of the energy of low frequency pulsations [2], taking into account their 3D character.

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ELABORATION OF NEW TRAVELLING MAGNETIC FIELD INDUCTORS FOR MIXING ALUMINIUM MELT

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MHD-stirring find wide application for preparing and purification of aluminium alloys. Processes intensification while stirring allow: 1) increase productivity of melting furnaces by improvement of heat-chanding; 2) decrease energy consumption for melting metal; 3) increase the metal quality by homogenisation of chemical composition; 4) prolongation of furnace refractory materials service time.

The melt mixing is realised by linear travelling magnetic field inductor with linear current load 100 kA/m and more Linear inductor is installed at the metallurgical furnace wall. The cannel (the pipe for liquid metal) is fulfilled in the refractory furnace wall. In present time are exploited inductors with coils, winded around the magnetic core. This inductors have high power consumption, complicated construction and high electromagnetic background. This electromagnetic background demands special defence equipment. More over, the coils, winded around the inductor magnetic core, together with travelling magnetic field produce pulsating magnetic field (solenoid type). It increases power consumption. The main goal of this work - new travelling magnetic field inductors elaboration for getting decreased power consumption.

In the article is shown, that right current load, produced by 3-phases winding, fulfiled of flat coils or of coils groups with active sides, put in the slots of magnetic core and winding around the teeth, permits increase energy characteristics of new inductors, decrease overall demention of MHD-stirrers, essentially decrease the background fields.

The main inductors energy dates (had gottem by experiment):

Parameter	Inductor with coils, winded across the core	New inductor
Supplying voltage [V]	380	380
Inductor current [A]	1070	680
Installed power [kVA]	720	435
Active power [kW]	82	54
Transformer current [A]	185	110
Pulling force (to the lead plate) [kg]	40	40
Gap (betw. inductor and plate) [mm]	60	60
Pulling force/active power [kg/kW]	0.48	0.74
Capacitors [kVAR]	700	440

For exact description of this devices the 3-dimensions mathematics model have been elaborated and tested.

Analysis of different schemes of winding have been carried out. Also, the shemes for realisation have been found. We have good correspondence of main calculated and experimental characteristics for new and early manufactured inductors. During experiments have been calculated and measured following characteristics: 1) phases currents (for fixed voltages);
2) power; 3) pulling force (to the lead plate); 3) induction in the gap; 4) magnetic fluxes in the in inductors core;

Have been confirmed (by experiments) the sufficient reliability of prognosis and improvement (up to 20-30%) of new MHD-stirrers.

UNIT FOR HOT DEEP GALVANIZING STEEL STRIP FROM THE MELT BASED ON USING MHD-SEAL

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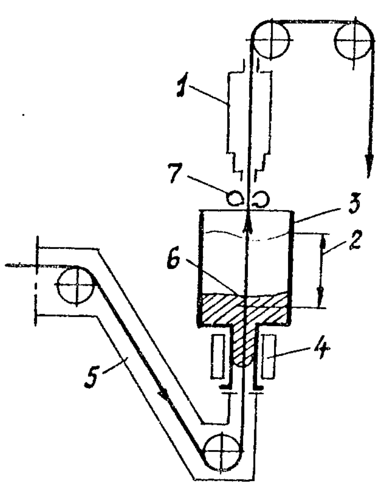
Existing units for hot deep galvanising steel strip from the melt consists of the pot with the melt, system of immersed and guiding rollers. This unit have some metallic parts, working in aggressive melt under severe conditions. Immersed rollers, guiding rollers, bearings, moving frame and other details are working under this conditions. Destroying of the steel elements in the aggressive melt leads to quick equipment wearing out and pollution of melt by ferrous metal. This reduces the quality of strip coating. Now the research works are carried out for creation of galvanising units without defects, have been mentioned above. One of such units is the unit "Vertical" (See fig.). The steel strip with preliminary cleaned surface is preheated in protective atmosphere and goes through the pot with melt in vertical direction from bottom to the top. During this treatment the strip acquires the demanded zinc coating. MHD-seal is designed for preventing of the melt leakage through the vertical channel (in cases of presence or absence of the moving strip in the channel). Except of mentioned parts the unit for hot deep galvanising has system for melting metal of coating and for feeding melt to the through-passing pot, system for normal (working) and emergency pouring off melt from through-passing pot, system for control of coating thickness (in case of the strip velocity is more 10 m/s). In this report are included the main tests results of experimental unit with MHD-seal I-1500 mm (for strip width up to 1500 mm).

The new meted (with using of through passing pot with MHD-seal underneat the bottom of the pot) have been tested with moving strip width 300 mm and during static tests with strip width up to 1200 mm on the experimental plant of CNIICHERMET (Moskow).



Technical dates of the MHD-seal.

1. Channel inner crossection (width x thickn.) - 1550x30 (mm)
2. Parameters of power system for MHD-seal;

2.1. Voltage 380/220 V, regulated;
2.2. Frequency - 50 Hz; 2.3. Active power - up to 180 kW;
3. Height of liquid zinc pillar, is sealing by MHD-seal in through passing pot - 0.6 m.

Fig. Principle scheme of unit "VERTICAL" for steel strip hot deep plating [1] : 1-unit for quick cooling; 2-level of melt; 3-through passing vertical pot for steel strip plating; 4- MHD-seal; 5-furnace for strip cleaning and preheating; 6-melt for plating; 7-unit for control of thickness of strip plating.

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EDDY CURRENT CALCULATIONS IN A SEGMENTED COLD CRUCIBLE

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Experimental results reported in literature show that instabilities on a surface of a charge in a cold crucible occur, corresponding to the periodicity of the structure.

In order to investigate the fundamental background of this phenomena, eddy current and electromagnetic force distributions in a cylindrical, segmented copper crucible containing an electrically conducting charge have been calculated.

The model consists of a primary induction coil, an azimuthally segmented copper crucible with insulating gaps between the 8 segments with 30 mm inside and 55 mm outside diameter and a cylindrical charge inside the crucible whose electrical conductivity is $\gamma = 0.8 \cdot 10^6$ S/m. The cold crucible and the charged are modelled as infinitely long in the axial direction. The height of the primary coil is finite. The copper segments are water-cooled, each segment has a separate water channel. Two extreme cases of boundary conditions between the charge and the crucible are considered: an ideal electrical contact and a thin insulating layer between them.

The calculations were performed using Vector Fields 3-dimensional finite element software Opera-3d for frequencies of 2, 10 and 50 kHz, corresponding to penetration depth of the electromagnetic field δ of 1.9, 0.9 and 0.4 mm in the crucible.

The results of the calculations indicate that there are high local eddy current densities near the outer surface of the crucible segments and near the insulating gaps due to skin-effect. The current density at the inner surface of the crucible adjacent to the charge is much lower than the current density near the outer surface.

Eddy current and electromagnetic force density distributions in the charge vary strongly with the azimuth. Local eddy current whirls occur near the insulating gaps.

By these calculations the instabilities are explained. The surface instabilities of the charge result from the non-uniform distribution of the electromagnetic force density along the circumference of the charge. The construction of cold crucibles can be optimised using computer-aided electromagnetic field calculations.

ESONANCE MEASURING METHOD OF QUANTITY OR LEVEL OF LIQUID METALS I METALLURGICAL MHD APPLICATIONS

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The electrical voltage resonance has been used for measuring of quantity or level of iquid metals by induction melting traditional or cold crucibles, by continuous casting slabs, thin slabs and strip. Main idea of method consists in using of phenomena of voltage resonance in RLC-electrical circuit that includes the electromagnet of MHD device as local inductance L. The electrical circuit work near resonance-point at the left or at the right of resonance-point - dependably from what is necessary: direct or opposite depends the current in induction system from level or quantity of melt. By change of quantity or height of liquid metal in induction system the inductance of magnetic system changes too. It is shown experimentally that secondary current in liquid metal could change up to 10 times by change the height of melt only at 10%.

Electrical properties of the system were investigated numerically and experimentally. Moreover a possibility of automatic control of melting or continuous casting was determined. The system doesn't need any special control system, for example, for providing of current increasing on inductors by grows of liquid metal level on electromagnetic crystallizer by continuous casting.

In the article the method of electrical parameters choice of resonance circuit was shown. The suggested system of control and measuring of melt level was tested experimentally.

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON THE MELT FLOW IN CHANNEL-INDUCTION FURNACES

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The lifetime limiting processes in channel-induction furnaces (CIF) like clogging, infiltration and mechanical wear are strongly effected by the turbulent melt flow in the induction channel. As well, the heat transfer to the furnace bath depends on the turbulent characteristics and intensities.

The experimental research revealed a complicated three-dimensional distribution of the time-averaged velocity field. The time-dependend fluctuations are mostly of a low-frequency nature. Therefore, the development of theoretical considerations is highly desirable to obtain some simplified theories for the interpretation and the valuation of the melt flow.

The integral transit velocity and its low-frequency fluctuations are mainly forced by density differences in the melt, resulting from the temperature distribution along the channel length [1]. The superposed electrovortical flow leads to a strong dependence on the geometry of the melt channel especially in the design of the mouth regions.

In the channel planes perpendicular to the channel axis the rotational electromagnetic forces initiate the typical double vortex flow patterns which are obvious in the lower part of the inductor. The spectral analysis of the measured turbulent flow field reveals, as it was observed in induction crucible furnaces [2], long term fluctuations of the local velocities with time periods in a range of 1 s to 10 s. The avoiding of these pulsations seems to be rather important because the friction forces as well as the build-up on the channel walls are strongly effected by them [3].

Numerical investigations point out, that the rotational electromagnetic forces and the related intensity of the flow in the channel cross-sections can be minimized by the modification of the shape of the channel cross-section area.

The theoretical modelization of the development of inertial wave propagations in rotating flow vortices allows the estimation of the period and the corresponding kinetic energy of these low-frequency fluctuations. The correlation with the experimental results is quite satisfying. In contrary, the numerical calculation of the time-averaged velocity field in the channel cross-section differs more remarkably from the measurements. The first k-ε-model used for the simulation of the flow didn't include assumptions about the low-frequency fluctuations. Nowadays the further development of the model in a more practical way reveals considerably better results.

By the theoretical analysis it is possible to develope practical rules for the lowering of the electromagnetically forced vortex flow in the channel cross-sections. The supplementary numerical description of the observed phenomena is valid. Therefore, the intensification of the thermal forced transit flow as well as the delaying of the build-up formation on the channel walls will be successful in the future.

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MODELLING OF MOLTEN METAL FLOW IN HYDRAULIC BRANCHING OF "TEE" TYPE WITH ASYMMETRIC DISTRIBUTION OF ELECTROMAGNETIC FORCES

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Hydraulic T-joint branching with asymmetric distribution of electromagnetic forces takes place in active operating zone of magnetodynamic pump. When supply currents with equal values and the same phases pass through the operating zone, distribution of electromagnetic forces is symmetric about longitudinal x-axis of central hydraulic branch of the "tee" canal, then the flow is symmetric and has vorticity on either side of the active operating zone in its regions, where the magnetic field decreases. Besides, the electromagnetic forces have, practically, only one x-component. Provided that the currents are asymmetric, x-component and y-component of the forces are of the same order of magnitude; moreover, the forces are distributed non-uniformly in the operating zone. Under such conditions complex asymmetric MHD-flows arise. They are of great significance for practical application.

The fact that flows under consideration are characterized by low values of magnetic Reynolds number Re_m, electromagnetic and hydrodynamic problems may be solved separately.

In this study, steady laminar flow of viscous incompressible liquid (two-dimensional formulation of the problem, plane case) has been investigated by numerical method at predetermined distribution of electromagnetic forces. Finite-difference method and splitting scheme have been used to solve Navier-Stokes equations for velocity and pressure. Computed distributions of metal velocity in the hydraulic branching of "tee" type have been obtained at different (in value and in phase) currents, supplied active operating zone of the magnetodynamic pump, and for principal operating conditions of the pump. It was shown that relation of rate of molten metal flow through different "tee" branches of the pump may be essentially changed.

Under laboratory conditions, investigation on influence of the change of currents relation on pressure distribution in outlets of "tee" branches has been carried out for physical model of operating zone of the magnetodynamic pump with molten gallium. Both results of this experimental investigation and flow patterns obtained for transparent electroconductive liquids by means of modelling have been compared with results of numerical investigations.

The described research was made possible partly by grant #30752 from International Science Foundation and grant #4.3.250 from State Fund of Fundamental Researches of Ukraine.

DISTRIBUTION OF ELECTRIC CURRENT AND ELECTROMAGNETIC FORCES IN WORKING ZONE OF MAGNETODYNAMIC PUMP AT ASYMMETRIC CURRENT SUPPLY

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A working zone of the magnetodynamic pump (MDP) is a hydraulic branching system of a "tee"- or a "cross"- type, in side branches of which the alternating currents I_1 and I_2 are generating, interacting in the cleatance of the electromagnet both with the proper field and the applied magnetic field. For estimation of the molten complex flows (which are of great practical significance), originating at the inequality of the currents I_1 and I_2, it is necessary to determine the distribution of electromagnetic forces in these cases.

The parameters of the working zones of the industrial MDP make possible to consider this task with a two-dimensional approximation without considering the movement of the metal and the skin-effect.

A numeral modelling of the distribution of currents and electromagnetic forces was carried out by the method of the finite elements using a principle of superposition. The distribution of the applied magnetic field is being described by the formerly obtained empirical dependences.

It is shown that the vector of the current density at a fixed point of the working zone is rotating in time. The hodograph of this vector is an ellipse, which in limiting cases degenerates to the circle or to the section of a straight line.

The vector hodograph of a specific electromagnetic force is the ellipse, which is turned through a certain angle and is shifted in space by a constant component of force to the hodograph of the current density vector

The methods of estimation of the current density, specific heat losses and a specific electromagnetic force under considered conditions are developed and realized by using a personal computer.

At the physical model of the working zone of the magnetodynamic pump the measurements of the distribution of the electric current and of the magnetic field are fulfiled, which confirmed the opportunity to use the developed computer model.

The research described in this publication was made possible in part by Grant N 30752 from the International Science Foundation and the State Fund of Fundamental Researches of Ukraine N 4.3.250.

CYCLOCONVERTORS IN MAGNETOHYDRODYNAMICS

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In the wide range of questions connected to the application of magneto hydrodynamic devices the problem of sinusoidal current source with prescribed frequency and amplitude is one of the most important.

Powerful cycloconvertors intended for magneto hydrodynamic devices of different kinds and destination have been already developed and put into exploitation.

Due the original design of such cycloconvertos it became possible to improve their reliability and to minimize their overall dimensions.

The above mentioned units make it possible to form output currents both in three-phase and two-phase orthogonal systems. In the case of necessity the development of systems with different number of output current phases and with preset phase shift. The rectangular form of output current is also possible.

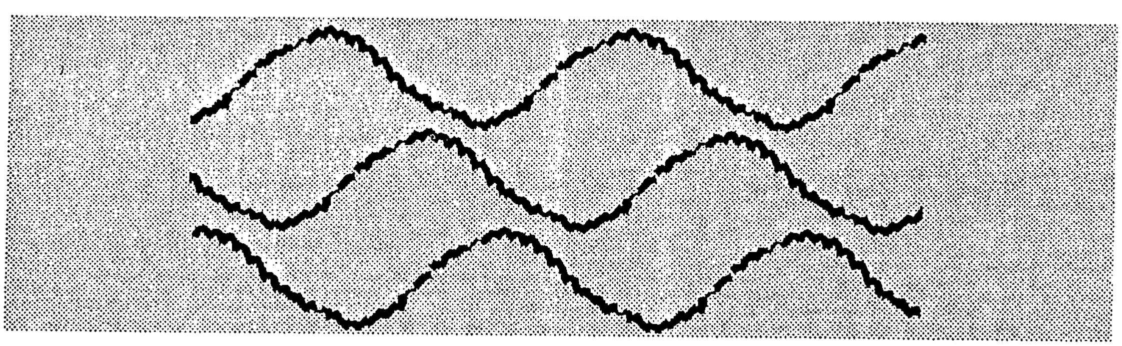
The units allow smooth regulation of output current value up to 1000 A and of the frequency of output current from 0,5 Hz up to 25 Hz with full correspondence of output signal to the prescribed value. Contactless reversing of cycloconvertor output currents is possible, which makes the reversing of magnetic field rotation direction of MHD-unit possible too.

The widest range of application fields is ensured by both using cycloconvertor and original design.

Most of MHD-devices need the frequency of output current up to 12.5 Hz. In such devices the use of zero circuit is possible, which, as compared to the bridge circuit, reduces the number of power thyristors in the converter twice.

The cycloconverter was tested as a part of MHD-device. The performed tests approved the reliability of the unit and full correspondence of all characteristics, including output current form, to preset values.

The output currents oscyllogramms of cycloconvertor, tested as a part of MHD-device, are shown at the figure below. The output current value is 270 A, frequency 4Hz.



Authors emphasize that special attention should be paid to the fact that the industrial production of such cycloconvertors is already possible.

VERIFICATION OF FLUXGATE MAGNETOMETER FOR HIGH TEMPERATURES

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Measurements of magnetic field as additional source for diagnostics are important for many liquid metal technological devices. Examples of such devices are aluminium reduction smelters [1] and liquid metal cooled breeder nuclear reactors [2]. High temperatures (500 °C - 900 °C) in these devices makes difficult usage of most traditional medium size DC magnetic field (up to 100 Gs) measuring methods such as the Hall effect based magnetometers.

Temperature proved fluxgate magnetometer was developed in Institute of Physics LAS, which can be applied for such fields. The magnetometer consists of high temperature sensor and room temperature electronic device. The fluxgate principle of field measurements [3] is based on nonlinear permeability of ferromagnetic materials applied in the sensor and compensation of the external field in it. The hotproved magnetometer sensor consists of prolongated iron core surrounded with single pick-up coil. Electronic registrating device dumps signals second harmonic in the coil via production in it compensating direct electric current proportional to external measurable magnetic field. The upper temperature limit or magnetometer is determined by Curie temperature of the sensor's ferromagnetic core and temperature durability of coils windings wire.

The sensor coils for the experimental magnetometer were made from different hotproved wires and cores of different electrotechnical steels, including pure iron. Sensor dimensions are approximately 15 mm diameter and 30 mm length. For tests and calibration the sensors were placed in non ferromagnetic stainless steel test chamber filled with argon and surrounded with stabilized electric heater. The test temperatures were up to 650 °C. The test chamber with sensors was placed in the center of two Helmholtz coils pairs oriented perpendicular one to another: vertically and horizontally. Helmholtz coils produced precisely calibrated external magnetic field of predefined strength and direction laying in the Earth magnetic meridian plane.

The sensors were tested and calibrated many times up to temperatures 600 °C and two weeks long continuous test experiment under 550 °C was performed. The correlation coefficient between the magnetometer output and applied magnetic field was stable and appeared to be 0.99997 ± 0.00002. The measured points with 95% probbility appears to be inside the error bars ±0.065 Gs, equal to 0,65% of main measure range.

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MHD LABORATORY WORKS FOR NON-FERROUS MATALLURGICAL APPLICATIONS

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During last 15 years MHD Laboratory has made several elaborations and starting up of MHD systems for non-ferrous metallurgical applications (fluid media-sodium, gallium, zinc, lead, alloy aluminum-zinc) with preliminary extensive theoretical and design development:

1.MHD unit for obtaining pure alcaline metals (rectification unit of Lovozersk ore mining and processing enterprise, Russia, 1980). Unit containes single-phase alternating current high temperature pump for sodium 500°C, flow rate 0,7 m^3/h, head 0,01 MPa. Pump works with energization by transformer and adjustable voltage source. Use the unit provides increase efficiency of pure level of metal.

2.MHD unit for gallium dosage in rough gallium system of Bauxitogorsk plant, Russia (1979).The unit consists of: a)induction linear 3-phase pump 0,72 m^3/h, 0,2 MPa: b) three dosage tanks with hoses and valves: c) electrical control system. The use of unit decreases the losses of gallium, improves conditions of work.

3.Similar gallium unit with dosage tanks 30, 40 kg and hight of lifting 4 m was manufactured in 1993, its starting up is planned.

4.MHD unit with a high temperature immersible linear induction pump for zinc and all another main electrical components has been developed and manufactured in 1985.The unit was meant for periodical pumping melted zinc out of a hot galvanizing pot into a reserve pot when there arises a necessity to inspect the walls of pot. The unit has worked successfully since 1986,i.e.for more then 8 years at a machine-building plant of Pervomaisk,Ukraine as alternative to mechanical ways of pumping. The melt elevation height is 3,8m,pump capacity 350 t/h, zinc temperature 460°C. The 500 tonnes pot emptying duration became 1,3 hours what is essentially less then it was before by use the ladle operation (24 hours).

5.MHD unit with a high temperature immersible induction pump for alloy aluminum-zinc and all main electrical equipment has been developed and manufactured by MHD Laboratory in 1993. Main difference in comparison with previous unit is in more agressive media (alloy 55% aluminum & 45% zinc) and in higher temperature- 620°C instead 460 C. The unit is meant for periodical pumping alloy out of hot pot into moulds. THe unit has worked successfully since 1993 at Cherepovets metallurgical plant, Russia. Plant ordered the another same unit in 1994. Maximum of alloy elevation height is 3,5 m, capacity 300 t/h, alloy's temperature is 620°C.

6. MHD unit for pumping and casting of lead with height lifting 4,5 m, capacity 200 t/h and lead temperature 600°C. Hot testing is planned.

MHD DEVICE FOR ALUMINIUM WEIGHING

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Modern metallurgy and foundry need devices capable to weigh liquid metal by small doses for producing small metal castings of volume 10 cm^3 and more. These castings are used as workpieces in the machine building under mass production of small parts, as granular aluminium deoxidizer for steel in ferrous metallurgy and in many other cases. Well-known MHD weighing devices designed on the basis of a travelling magnetic field [1] or magnetodynamic pumps [2] are not capable to weigh liquid metal by small doses. On the other hand, the so-called MHD granulators [3] can produce castings (granules) of volume of up to 1 cm^3, not more.

In the Institute of Electrodynamics of the Ukrainian Academy of Sciences the MHD device for weighing liquid metals has been designed. This device is intended for obtaining a granular aluminium deoxidizer of 20 mm in size and more. The device consists of AC or DC magnet, in the air-gap clearance of the magnet there is a channel. It is open in the top and has holes. A liquid metal in the channel is affected by the electric current induced by two electrodes. Correlation of this current with magnetic field of the magnet causes electromagnetic forces which keep the liquid metal in the channel. When the channel is disenergized or the current polarity is reversed the liquid metal flows out of the channel through the holes in the bottom. Thus, it is possible to obtain different doses of metal by alternating the action of electromagnetic forces on metal and by changing the duration of this action.

The dosed metal is cooled and solidified in the movable mould designed as a closed metallic band composed of specific components (plates). The plates have recesses on the surface to where the liquid metal is poured. Thus, the shape of the obtained castings is determined in this case by the shape of the recesses while their size depends on the time of the metal outflow. A specially designed control system allows outflow of the metal only when recesses of the mould are located directly under the holes of the channel.

This MHD device is experimentally tested by using gallium as a model metal. The tests have shown that this device may be successfully employed not only for the above purpose but also for weighing liquid metal in the foundry conveyors, for feeding metal into the foundry automatic machines and others.

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BEHAVIOR OF WAVE ON MOLTEN METAL SURFACE UNDER THE IMPOSITION OF HIGH FREQUENCY MAGNETIC FIELD

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A magnetic pressure which suppresses a metal inward is one of the functions of a high frequency magnetic field and has been utilized in various metallurgical processes such as E.M.C. and a cold crucible. These processes can provide a smooth surface since a free surface is stably held during solidification by use of the magnetic pressure. However, this advantage often disappears when the external disturbance such as feeding of raw materials causes perturbation on molten metal surface. Therefore, the behavior of the wave on the surface under the imposition of the high frequency magnetic field is crucial problem in practice.

The effect of a static magnetic field on the small perturbation has been investigated by many researchers and the damping behavior of the perturbations has been clarified. On the other hand, the effect of an alternating magnetic field on the perturbation has scarcely been studied due to experimental difficulty , especially the difficulty of generating a uniform magnetic field.

In this study, the damping behavior of the small wave under the imposition of the high frequency magnetic field has been studied. A small standing wave was generated mechanically on the surface of a molten gallium. The amplitude of the wave was measured and analyzed to get the spectrum by using a FFT analyzer. Furthermore, from the evaluation of the damping constant due to the alternating magnetic field, it is found that the high frequency magnetic field has a function suppressing disturbances on the molten metal surface.

ELABORATION OF SPIRAL INDUCTIVE - CONDUCTIVE PUMP

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The inductive - conductive pumps (of a double - feed type) are MHD - devices. The characteristic features of the inductive pumps, having the travelling field, integrate with those belonging to the three - phase a. c. conductive pumps.

The spiral inductive - conductive pump consists of a frame, spiral channel, made of heat - resistant 20X18H10T non - magnetic steel, three symmetrically placed around the channel a. c. magnets, three symmetrically arranged transformers whose secondary high - current windings are short - circuited by the spiral channel faces.

When the three - phase voltage, 50 Hz, is fed into exitation coils of the magneto and into the primary windings of the trasformers, the travelling magnetic field, that induces axial rotable field of the inductive current density, becomes exited in the liguid metal which fills up the channel. The same occurs with respect to the conductive current density of the rotable field. If the inductive and conductive fields of the currents density are phase coincident, the electromagnetic pressure, developped by the pump, reaches the maximum value. Since the fields of the electromagnetic volume forces, created by each of the conductive modules, are out of phase within 120 degrees, the resulting pressure has a weakly marked pulsation component.

Failure of one of the modules or de - energizing of one of the phases of the pump feeding voltage causes reduction of the pressure generated by the pump. Nevertheless its serviceability remains. The designed pump makes it possible to carry out speedy repairs of one of the transformers or the magnets without switching off the whole pump.

The electromagnetic processes in the pump's channel are decribed by the following dimensionless equations

$$\frac{\bar{\omega}}{2\pi}\frac{\partial \vec{a}}{\partial \tau} - \bar{\omega}[\vec{v}, rot\vec{a}] = \Delta\vec{a}, \tag{1}$$

$$\frac{1}{r}\frac{\partial \vec{a}}{\partial \varphi} = \begin{cases} e^{2\pi i[\tau-(n-1)/3]} & \text{— on the poles of magnet,} \\ 0 & \text{— out of the poles,} \end{cases} \tag{2}$$

$$\frac{\bar{\omega}}{2\pi}\frac{\partial \Phi_э}{\partial \tau} - \Delta\Phi_э = 0, \tag{3}$$

$$\frac{\partial \Phi_э}{\partial z} = \begin{cases} \delta_z e^{2\pi i[\tau-(n-1)/3+\alpha]} & \text{— on the electrodes,} \\ 0 & \text{— out of the electrodes.} \end{cases} \tag{4}$$

The developed pump is intended for pumping liquid – conductive media, in particular such as liquid metals in cooling systems of nuclear reactors. A test specimen of the pump, designed for pumping of liquid tin and lead at the temperature of 500° C, is able to generate the pressure of about 0.15 MPa, the pump capacity being up to 1 litre per second. The voltage – current characteristics of the transformers and magnets, and the values of the magnetic induction, developed by the electromagnets, are in satisfactory accordance with those of the design.

ABOUT THE SIMULATION OF THE PROCESS OF FLUID ADHERING TO A MOVING WITHDRAWN SURFACE

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Many technological processes have to do special material adhering to a product surface. For example, this problem is important for the magnetic tape produce, wire adhering etc. For the surface that is withdrawn from molten metal or other liquid material there are problem of the film profile determination. This problem is the subject of our work.

We consider some mathematical modelling problem of the adhering process of the viscous liquid film to a slowly moving vertically withdrawn from molten metal or other fluid capacity surface. It is well known that the thin liquid sheet on the withdrawn surface decreases by removal from capacity surface and it has tendency to the constant thickness determined by the surface moisten quality, its moving velocity and physical properties of fluid: viscousity, density, surfase tension coefficient etc. We suppose that the fluid is newtonian and the withdrawn process is isothermal. Gravitational forse acts against the surface moving direction and it could be organised by the cross E and H fields also the electromagnetic forse acting whether against (parallel) to gravitational forse or normally to the withdrawn surface. It will be supposed the fluid film flow hasn't any influence on the electromagnetic field.

The peculiarity of the problem is two different flow regions: film flow on the mowing surface and meniscus region which are recirpocity crossing. Therefore this problem was inwestigated usually independently in two over named regions with the following sew of these solutions together. But this approach complicates the problem analysis and parameters determination that could be using for the process control. The film flow works analysis shows that film flows effected by gravitational forces have many different regimes including solitary waves and are marked by nonlinearity. This facts influence very much on the surface covering quality.

The investigating film flow class is now almost unknown becouse it has two specific peculiarity: the flow is going against the surface mowing (vortex flow) and the static meniscus determines flow beginning. We obtained one whole equations system describing the process. That is the system of two partial differential equations for the free boundary surface profile (x, t) and some introducting special function f(x, t) describing the velocity profile alteration.

The electromagnetic force assumed known at first as the general case is more complicated. This approach gives some possibilities to analyse the process of the fluid adhering to a moving withdrawn surface and to search electromagnetic control principles of the system.

RETURN-TRANSLATION MHD-TRANSFER OF THE ELECTRODE DROPS UNDER ELECTROSLAG WELDING*

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Traditional electroslag welding, almost always is accompanied by over expenditures of electric current to the non uniform melting of the welded edges. Such non uniformness is caused by the concentrated heat emanation in the central axis part of the bath. Uniform heat inclusion, which is necessary for complete minimal melting of the edges, has been done by return-translational movement of the electrode along with the mechanism of its supply /1/. Unfortunately such mechanism complicates the construction of the welding plant and worsens the stability of welding.

By applying MHD-methods the return translational transfer of the electrode metal along the welded edges with the moveless position of the electrode has been studied. This effect is reached by the presence of one or two conductors with the electric current, placed near the back side of the weld developing surface. In case two conductors, which are placed at the opposite developing surfaces are used, the managing current is passed in turn through each of them. In case only one conductor is used, the direction of passing current is changed to the opposite periodically with the given frequency

Welding of the technical titanium BTI with the width δ=60-120 mm has been conducted with the traditional central position of the wire-type electrode, through which the welding current I_1 passes. Below we present the values of the linear welding energies without return-translating movement of the electrode metal /g_{n1}/ and with it /g_{n2}/ :

δ=60 mm	g_{n1}= 31 kwt-h./m	g_{n2}=26 kwt-h./m
δ=80 mm	g_{n1}= 42 kwt-h./m	g_{n2}=34 kwt-h./m
δ=100 mm	g_{n1}= 51 kwt-h./m	g_{n2}=41 kwt-h./m
δ=120 mm	g_{n1}= 61 kwt-h./m	g_{n2}=47 kwt-h./m

As it follows from the presented figures, minimal uniform melting of the welded edges, conducted by means of the welding in the external field, is a source of the 12-23% economy of the linear energies of welding.

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THE ELECTROMAGNETICALLY CONTROLLED VELOCITY OF THE LIQUID METAL ROTOR ROTATION IN MHD-UNIT

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The MHD-drive is considered,in the liquid metal rotor of which the direct electric energy transformation to the heat and the mechanical energy of the rotating electroconductive liquid with the polydispersed inclusions occurs. The efficiency of the molten aluminium rotative movement control for realizing the liquid metal refining process is experimentally investigated.

The influence of the angular velocity change of the molten metal in the channel of the MHD-unit on degassing and mechanical properties of aluminium alloys is determined.

THERMOCURRENTS AND MAGNETIC FIELDS AT INTENSE LOCAL SURFACE COOLING OF MOLTEN AND SOLID METALS

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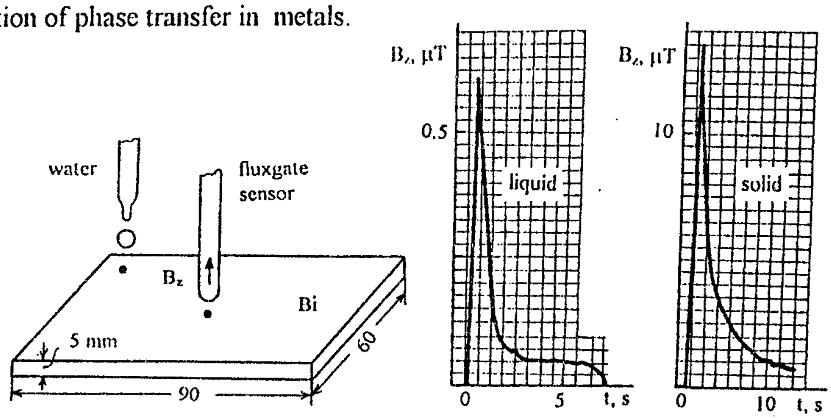
In a number of our previous experiments on thermoelectric phenomena at melting and solidification a non expected effect was fixed - generation of sharp magnetic field pikes against the background of in general smooth time dependencies. As a rule, these pikes correspond to the intense non stationary initial stage of cooling. The interesting to us physical conditions were reproduced in a very simple way - the surface of a metallic *Bi* specimen (see Fig.) was exposed to falling $d \approx 3$ mm water drops, evaporating in approx. a second and dissipating ≈ 100 cal of energy each. Both in the cases of molten or solid state, at temperatures somewhat over or below the melting point $T = 271$ °C correspondingly, each water drop resulted in a measured outside the specimen magnetic field pulse. In both cases the dependence of the generated field on time remain similar, with approximately the same width of the pike equal to a few sec. This value is of importance since different non stationary temperature field approaches must be compared. In the same time, when the drop falls on a solid surface, the amplitude of the pulse is higher by an order.

The model of the phenomenon seems more transparent, when the drop meets a molten surface. Under the evaporating drop for a few seconds a floating solid (diameter $\approx$ 1 cm, thickness $\approx$ 0.2 cm) islet appears, defining a sharp enough boundary between liquid and solid states with different coefficient of thermo-emf. α. Proposing a *grad T* along this boundary $\approx$ 10 °C/cm (a number of reasons for this can be discussed) and assuming that electric resistance is concentrated in the body of the solid islet the measured values of the field can be explained. In the case of a fully solid body one of the explanations can be based on ideas about strong dependence of α on the state of mechanical tensions. Estimates show that in this case the thermoelectric power generating zone where *grad T* and *grad* α have orthogonal components in thicker and much more diffuse.

Experiments with molten and solid *Ga* give similar results. Numerics on typical to the problem temperature fields show that it is not easy to find temperature gradients strong enough for a general explanation of the phenomena.

In [1] we forwarded the idea that thermocurrents can be generated in the dendrite zone at solidification. In [2] thermoelectric effects in an industrial continuous steel casting stand and experiments on field generation in solidifying *Cd, Zn* and *Bi* were described. Results of this paper confirm additionally the general conclusion that magnetic field measurements can be used as a tool for investigation of phase transfer in metals.



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THE ADVANCED STIRRING METHOD OF MOLTEN METAL FOR CONTINUOUS CASTING OF STEEL

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The high power consumption and the intricacy of unit making use of rotating and traveling magnetic fields for stirring of the residual molten metal in continuous cast slabs has resulted in development of more simple method with energetically more effective conductive way to produce a stirring motion. The Lorentz forces generated by interaction of the direct electric current, flowing along the length of the slab, and the magnetic field of electromagnet, which is perpendicular to the slab axis, are used for stirring. The electric current is imposed on one side to crystallizer and on the other side to the slab in the spot, where the molten metal zone is not occurring. The first industry application (ŽP Podbrezová, a.s.) of this method has the duplicate current supplies; in the molten metal zone they are realized by roll segment "0" on the crystallizer and by the first row of guide rolls, below which the electromagnet is situated. The second current supply is also realized by two rows of the working rolls.

The character of molten metal's stirring motion produced by Lorentz forces is determined by the spatial distribution of pressure and the magnetohydrodynamics laws. Beside the stirring of molten metal, more other factors brought about this method, which are more effective, are taken part in the influence of solidification process. A pool of liquid steel with solidification front is not a compact conductor, but from the electric point of view it is a complex of big quantity of free mobile elementary conductors with the different electric conductivity and in consequence the non-uniform electric density distribution and the intensity of generated Lorentz force on the area of electromagnet action. Thus, the action of force is localized on the area, where the microvolumes or objects with the different electric conductivity in comparison to their surroundings, like inclusions, solidifying metal and the melt zone on the solidification front with higher concentration of elements. The complex of Lorentz force has produced a mechanisms effectively affecting on the process of primary structure formation and a distribution of structure components. The direct current made by an recticifation has always the pulsating component, which magnitude depends on the type of the rectifier and the method of control. The pulsating character of forces does not decrease the efficiency of stirring motion generation. It influences positively on the macrostructure formation and suppresses the formation of the internal porosity. Magnetic field itself, in presented considerations taken only for an interelement necessary to produce Lorentz forces, is another factor actively intervening in solidification process. It shifts the temperatures of phase transformations of steel's primary crystallization toward lower values and affects on their kinetics overall and so intervenes in the thermodynamic conditions of solidification.

The experiments in practice has shown it is satisfied one electromagnet and the flow velocity smaller than 1 $m.s^{-1}$ for sufficient refinement of the structure in the 200 x 200 mm slab. This velocity has already enlisted the transport of molten metal from the zone of the electromagnet action, where the magnetic field affects on the liquidus temperature. The magnetically modified molten metal is solidifying under more favorable thermodynamic conditions in the decisive parts of slab cross-section.

FREE SURFACE PHENOMENA AND FLUID FLOW IN ROTATIONAL ELECTROMAGNETIC STIRRING OF A METALLIC MELT

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Even though the numerical methods and computational capabilities of the computers have developed considerably during the last 10 years simulation of the free surface still is - especially when drastic and rapid shape changes are involved - a challenging and problematic task. Until recently it has not been possible to take into consideration simultaneously the free surface behavior and the applied electromagnetic forces while solving for the fluid flow of a liquid metal.

This paper reports the results of a research on the behavior of a metallic melt under the influence of rotating electromagnetic stirring. In this study the free surface deformation and fluid flow under the influence of electromagnetic stirring were studied using both computational and experimental methods.

A commercial computational fluid dynamics package was modified by introducing user made subroutines into the code to simulate free surface deformation and the fluid flow in rotational electromagnetic stirring. Results of the computations were compared with the observations in the experiments.

A laboratory scale experimental apparatus was constructed consisting of a helically wound armature, a variable frequency drive, and transformers. The magnetic fields inside the stirrer were measured using a search coil and a Hall probe. The free surface deformation and the local velocities with in the rotating melt were measured. Also the time scale of the transition from rest to the steady state due to stirring was defined. Comparison with the computed results showed good agreement.

The effect of the electromagnetically induced fluid flow on the solidification structure was also investigated. Structures of stirred and non-stirred samples were studied by using optical microscopy and SEM.

DISINTEGRATION OF MOLTEN METAL JET BY MEANS OF THE USE OF REPETITIVE PULSES OF MAGNETIC FIELD

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Proposed method for disintegration of molten metal jet may be used for problems of vacuum refining of melt, for more uniform distribution of received metal in the inlet of continuous-casting mould, etc.

This work is a continuation and development of disintegration way examined before*) . Contactless method for jet disintegration submitted in the work is based on the action of two mutually orthogonal magnetic fields (i.e. stationary field and pulsed repetitive field) on the jet. Vectors of the fields are in a plane, which is perpendicular to traffic direction of the jet. Atomization of molten metal jet arises from electromagnetic moment of short duration, which leads to rotation of metal portion in active operating zone of inductor. Emergence of this moment is a result of interaction between eddy currents, induced in the metal by action of pulsed magnetic field, and external stationary magnetic field. For the sake of continuous disintegration of molten metal stream, pulse recurrence frequency must be in agreement with velocity of metal motion in the stream.

In the course of theoretical and numerical investigation:

— electromagnetic processes in a small volume of molten metal, which is under the combined action of pulsed repetitive magnetic field and stationary field, have been studied;

— optimal parameters of pulse magnetic field (such as pulse length, pulse amplitude), when molten metal portion the most effectively accelerates to desired angular velocity of melt rotation, have been defined;

— specific graphic dependences have been obtained to determine and to choose the optimal field parameters in the case of disintegration of molten metal jets with different diameters and jets made of various materials.

The theoretical results may serve for development of a new pulse magnetic technique for disintegration or atomization of molten metal jet.

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MHD-UNITS FOR PREPARING AND CASTING OF IRON

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More than 20 years the MHD-units of a magnetodynamic type has been used at the foundry shops for iron casting into the molds. The long-term experience of operation has confirmed their high working ability and made possible to start the development of the novel technological processes using these units. In particular it was possible in a new way to approach to duplex-process arranging for preparing and casting of metal at the iron foundries.

By the traditional scheme of the duplex-process which provides the use of a mixer only for heating and holding of cast iron; casting of iron being provided with ladles of special pouring devices; the additional overflowing of metal is inevitable, which results in reducing of its temperature. To compensate these heat losses the iron in the mixer is to be overheated, which causes the increase of total power expenditures and worsening of the quality of castings.

The most effective and economical scheme of the duplex-process is the version- a cupola-MHD-mixer of a magnetodynamic type; since the MHD-controlled metal flowing in its channel permits during a periodical feeding of metal into the mixer to realize the given its overheating and the continuous proportioning filling of molds. In this case a significant reduce of a power expenditure is achieved, the coke expenses and sulphur contamination of cast iron are reduced, the melting equipment efficiency is increased; the conditions for manufacture of thin-walled qualitative castings from cupola-melted iron being developed, including the ductile iron.

The characteristics of a new gamma of the MHD-equipment for heating, treatment and pouring of iron on the continuously moving and pulsating casting conveyers with a useful volume of 1600-6300t are listed. The metal design of the mixers is unificated and provides the opportunity to use the changeable induction units the power of 160, 300 and 600 kW, which permits to carry out the heating of metal within the mixer by 100-200°C.

In comparison with an ordinary ladle-pouring this version of the duplex-process yields the economy of the energy power to 200 kW.h for one ton of cast iron.

THEORETICAL INVESTIGATION OF INFLUENCE OF TRAVELING MAGNETIC FIELD INDUCTOR PARAMETERS ON THE FORMATION OF INGOT CASTING STRUCTURE

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Ingots quality increasing - actual problem for metallurgy. Ingot formation depends of casting machine parameters, properties and state of hardening melt and so on. This determines the structure of ingot casing and its complete quality: mechanical properties, rate of chemical and physical un homogeneity and so on. The state of melt in the liquid core of ingot just before its hardening, is very important. It is necessary to aspire to maximum chemical and physical homogeneity of the melt. It may be reached by mixing the melt by different ways. In this work the mixing is investigated by travelling magnetic field inductor.

The inductor is put on the crystallizer wall. After switching it creates electromagnetic force for moving of liquid metal. This force may be divided to 2 components: pulling along the wall and pushing away of the wall. The both components of electromagnetic force density are decreasing according the distance to inductor (z) by law: **exp(-z)** and in the middle of crystallizer the force is minimal. This liquid metals is accelerated along the inductor wall from up to down, but on some distance (closer to the axis of crystallizer) moves from down to up (in reverse direction). Upper part of liquid is limited by hard surface, lower pat - by hardened phase. The both surfaces are essentially removed of inductor.

The melt movement are modelled by 2-dimensions border task. Inside learning area, the movement is calculated by equation of isothermal laminar movement of electro conductive liquid and condition of liquid untiring. The electromagnetic force density is connected with inductor parameters and regime of power supplying. On the hard border there are conditions of sticking to the walls and absence of leakage's along the walls, and on the axis of symmetry - equality to zero normal (to the symmetry axis) component of velocity.

Border task for velocity components transforms to border task for vortex and current functions. The last task is calculated numerically. For chosed net the equations of border task approximate by finite-difference schemes. Received system of algebraic equations may be solved by one of modificated methods of Gauss-Zeidel-Limban. Velocity distribution is determined by current function distribution.

The velocity distribution is very important factor, having influence to the melt homogeneity. Coefficient of heat-change on the border of hardening is calculated by using of melt velocity. Authors have created calculating methods and programmes for determination of growth velocity of ingot casing in area of mixing and ingot mechanical state. Dimensions of structure elements (grains) are depended of melt hardening velocity. It is necessary to aspire to constancy of the characteristic on all front of hardening. Received results show the influence of travelling magnetic field inductor, situated under the crystallizer, to ingot homogeneity and the dimensions of grains.

MAGNETODYNAMIC FURNACES WITH AN OPEN CHANNEL FOR PRODUCING ALLOYS WITH THE ALMOST UNSOLUBLE COMPONENTS

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Preparation of alloys, the components of which are considerably different by the physico-chemical properties (the temperature of melting, density, etc.) is realized in serial magnetodynamic [illegible] units with a number of restrictions. First of all it is connected with stability of lining, overgrowing of a channel, viscosity, density and electric conductivity of the alloy. Besides, the hit of unsoluble lumps of the refractory charge into the channel causes difficulty of heat transfer from the channel to the basic bulk of the additives, introduced into the crucible. A free approach to the channel system in the process of work for control and refinement is provided by an opened horizontal channel. The controlled process of introduction and dissolution of the additives in the opened channel, where the intensive electric vortex-type (rotational) flows are operating and heating of charge is being additionally realized by the electric current of a high density, makes possible to accelerate considerably the alloy's production and widen their nomenclature.

To produce the aluminium-based alloys with the most unsoluble additives a number of constructions of the single-turn magnetodynamic furnaces of the inductor power 25 kW is developed, some characteristics of which are given in the table below.

alloy	Temp.-re of a molten metal, °C	Furnace capacity, kg	Channel lining	Ratio of an opened part of a channel to its general length	Aver. density of current in an opened channel, A/mm²
75%Al +25% SiCa	950	60	vologran	0,6	2,5
		70	shamot	0,7	2,5
75%Al+ 25% SiCaFe	1060	90	shamot	0,9	2,8
26%Al +74% Mn	1300	120	shamot+mullito-corrundum	0,8	1,7
50%Al +50% FeMn	1400	100	mullito-corrundum	0,9	2,5

The electric vortex-type flows in the channel are most intensive in the zones of transition from closed sections to opened ones and introduction of additives into the molten metal is realized to these zones. Pouring a molten metal from the channel into the crucible of the furnace along the metal manifold by means of the electromagnet accelerates the dissolution of additives and averaging the chemical composition of the alloy.

To provide high power indices of the work of magnetodynamic furnaces in their construction and in the systems of power supply the opportunities of compensation of change of electric conductivity of the alloy during its preparation are provided.

On the base of obtained results the furnace with power of 50 kW for melting aluminium alloys with refractory components is being developed.

ELLECTRICALLY INDUCED VORTICAL FLOW ROLE IN ELECTROSLAG WELDING AND METALLURGY*

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Indiscriminatingly, therefore spontaneously EVF have existed during decades in electroslag process of welding and melting. The impossibility to control EVF in the most cases made technical-economic indexes of these technologies worse. During the welding and melting of metallic materials, such an EVF became a reason of unfavorable transverse growth of large scale crystals, of defective zones in the axis of melted metal formation and shaping of its physical and chemical heterogeneity /1/.

EVF control by the longitudinal-diametrical magnetic field, that constitutes an induction in the zone of welding 0.05 - 0.07 Tl, allows to provide a high quality of welding wares by wire electrode, with the length of joints about several meters. It is attainable at account of shallow metallic bath homogenous grainy metallic joint. Such an electrical-vortices convection allows to guarantee a high quality of metal under the maximum speed of welding, that reaches 9 m/h /2/.

A control over EVF by laying on a zone of welding or melting a diametrical magnetic field provides a homogenous grainy structure of metal. It is attainable at account of reflexive-progressive vibrations of bath in a horizontal direction. It is technologically profitable to use such a controllable EVF during the welding of compact wears and melting of ingots /3/.

EVF, which form in the baths of three-phases three electrodes thermoore furnaces like RKZ and SKB, represent a special kind. The cyclical method of immersion of the electrodes in melt, which provides an even heatmassexchange over the whole volume of the mass, has been suggested in order to decrease expenditures of electrical energy and increase the productivity of melting of slags and fluxes in 1,5 - 2 times and reduce the expenditures of electrical energy on 16 - 18% /4/.

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ELECTRO-MAGNETIC CONTROL OF GAS BUBBLES INJECTED INTO MOLTEN METAL

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In the refining process of a metal, various gases are used to remove inclusions and harmful elements from the molten metal. For the improvement of a removal rate, the gas is required to be injected as fine bubbles. A novel method to control the bubble size of the gas injected into a molten metal was developed by means of electro-magnetic force.

It is well-known that the interaction of an electric current with a magnetic field produces a body force. If the induced force is parallel to a gravity force, a conductive material changes its weight effectively according to the intensity of the electro-magnetic force. In this sense, this force is called electro-magnetic gravity. To confirm the effect of the electro-magnetic gravity, static electric and magnetic fields were applied to mercury, and change of apparent specific weight of mercury was measured.

The electro-magnetic gravity affects the formation of gas bubbles, as the volume of the gas bubbles separated from the orifice in the molten metal is governed by the balance between buoyancy force and surface tension, . Bubble formation was studied under various electro-magnetic conditions. Nitrogen gas was injected at a fixed gas flow rate from an orifice attached at the bottom of the mercury bath. Alternating electric field with various frequencies were imposed perpendicularly to static horizontal magnetic field. at several levels of the intensity, and the number of bubbles formed in a certain period was measured.

Experiments revealed following results: (1) Apparent specific weight of mercury changes with electro-magnetic force. When the force is in the same direction of gravity, the weight increases and it is in the opposite direction, the weight is decreased, as is expected. (2) The interval of bubble formation could be completely synchronized with the frequency of the applied alternating electric field, if the imposed intensity of the electro-magnetic force was appropriate value. (3) By increasing the frequency, average size of the bubbles could be reduced. For example, the number of 6 bubbles/sec without any electro-magnetic force increased to 40 bubbles/ sec under the alternating electro-magnetic force at 40Hz.

Theoretical discussion was also carried out on the interval of the bubble formation.

COMPUTER SIMULATION AND EXPERIMENTAL DETERMINATION OF FREE MELT SURFACE IN AN INDUCTION FURNACE WITH COLD CRUCIBLE

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Introduction. The paper presents calculated and measured results of the electromagnetic (EM) field distribution and the shape of the free surface of the melt in an induction furnace with a cold crucible (IFCC). The experiments on a pilot IFCC which show the influence of the supplied power on the melt shape and the integral characteristics of an IFCC are described.

2D mathematical model of the EM field in an IFCC. The melting process in an IFCC depends on the distribution of the electromagnetic field. The structure of the EM field is 3-dimensional because of the slits in the metallic crucible [1]. The frequency of the inductor current is in the range of several kHz and leads to the distinct skin effect. Although the EM field in an IFCC is 3-dimensional, it is possible to describe the field in the systems with narrow slits by the simplificated axisymmetric 2D model [1]. This model determines the magnetic field by the azimuthal component of the vector potential **A** in the outer space and by the scalar potential F of the magnetic field in the slits of the crucible. The connection of both fields **A** and F on the boundary of the slit is predicted in the vertical cross-section of the set-up by the field transparency parameter K.

Axisymmetric modell of the free surface. The free surface of the melt has a strong influence on the heat transfer and the skull shapes in an IFCC [2]. The surface shape is strongly coupled with the electromagnetic field and, as a consequence, with the design of the cold crucible and the inductor. The efficiency of an IFCC depends on the shape of the melt surface because of the heat generation in the melt and the heat losses at the the melt surface. As it is complicated and rather expensive to measure the shape of the melt under the industrial conditions, numerical simulations and experimental studies of the behaviour of the melt are necessary. The shape of the free surface of the melt is governed in hydrostatic approximation by the normal-stress balance, i.e. by the Laplace-Young capillary equation with a EM force. The calculation starts from the assumed meniscus shape. Then the shape of the free surface is calculated by shifting the unknown surface considering the EM field corrections.

Experiment. Experiments have been performed with a pilot IFCC on samples of aluminium and the intermetallic compound Ti-Al. The furnace is set in a vacuum chamber. The generator supplies AC power up to 250 kW with 10 kHz. The water cooled copper crucible has 26 segments that are connected with the water cooled copper foot. The laser beam scanning method is used to determine the shape of the free melt surface. The effects of the power and other process parameters on the shape of the free surface are demonstrated. The numerically simulated shapes of the free melt surface agree well with measured ones.

Conclusions. The results of the experimental determination of the free melt surface in an IFCC confirm the mathematical model. Therefore the developed mathematical model is useful for the optimal design of electromagnetic casting systems using cold crucible and can favour the industrial applications of this new technology.

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Crystal Growth

NUMERICAL SIMULATION OF HYDRODYNAMICS AND HEAT/MASS TRANSFER IN THE BRIDGMAN PROCESSE UNDER THE EFFECT OF A ROTATING MAGNETIC FIELD GENERATED BY AN INDUCTOR OF FINITE LENGTH

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The problem of an efficient control of hydrodynamics and heat/mass transfer in the Bridgman process under the effect of a rotating magnetic field (RMF) on the melt and solidification front has been discussed in some papers, e.g. [1,2]. But a great deal of known papers analyze the action of the RMF generated by an inductor of infinite length. In practice the above phenomenon might not be achieved. So, the problem under study should be considered with account for a confined length of the RMF inductor.

The present paper gives the results of a numerical simulation of the RMF action on hydrodynamics and heat/mass transfer in the Bridgman process considering the case of a "short" inductor of RMF with account for a magnetic field of forebody parts of the inductor's coils. The paper presents data on the RMF action on hydrodynamic characteristics and heat transfer in a liquid phase, heat transfer parameters at solidification, as well as the effect of RMF on the interface change. Temperature fields in the melt and in the solid phase and their change at different parameters of solidification and MHD effect have been investigated.

Study of hydrodynamic patterns, temperature field and solidification front has been conducted applying the solution of a conjugate problem of the Navier-Stokes equations and the equations of heat conductivity and electrodynamics. Here, a convective transfer and solidification heat (included in the coefficient of effective heat capacity) are taken into account in the equation of heat conductivity [3].

The equations of hydrodynamics and heat conductivity have been solved by the finite difference method. The motion in the solid phase is stopped by indroducing a large viscosity coefficient. The method described in [4] has been used for electrodynamics calculation.

The results obtained are compared to the variant of action of RMF of infinite length, and both are being estimated from the point of view of their similarity to a real process. In particular, the proposed numerical model allows to account for asymmetry of the RMF inductor location with regard to the device height as well as to account for more complicated solidification conditions, and many other factors.

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GRADIENT FREEZE CRYSTAL GROWTH WITH OPTIMIZED CONVECTION INDUCED BY A ROTATING MAGNETIC FIELD

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The principle of crystal growth from melt by the gradient freeze technique is leading a dynamic temperature field over the sample without any movement of the furnace or the sampie. As a result the crystals have a low etch pit density (epd).

For all crystal growth procedures from melt, hydrodynamics processes have a fundamental influence on the crystallization process and therefore on the structural quality of the crystals, the homogeneity of distribution of dopants and impurities, the morphology of the phase interface and the maximal crystallization velocity.

If special means are applied, e.g. by use of an alternating magnetic field, the parameters of crystallization can be affected.

Such additional opportunity for an active transfer process control in the melt provides a principal possibility to achieve optimal (from the technological point of view) parameters of the growth process.

In this poster a new developed multizone gradient freeze furnace with a magnetic system for the rotating magnetic field induction will be presented. So it is possible to forced a rotating motion in the semiconductor melt and to study the effect of forced convective flows in the melt on the heat/mass transfer parameters, shape of the solidification front, etc. The results of study of the effect of a rotationg magnetic field on non-stationary hydrodynamic characteristics of the forced convective flows and oscillations in the melt are of a special interest, too.

The effects of the rotating magnetic field on the crystal growth of III/V semiconductors by the vertical gradient freeze technique will be compared to the calculations and results of the model experiments.

The data obtained can be used for analysis of optimal ratio of the configuration of a temperature profile in the melt, intensivity of the melt electromagnetic rotation and growth velocity of the solid phase.

The investigations contribute to preparing microgravity experiments, to examine the crystallization process with forced melt motion without superimposing by the natural convection. Besides, they additionally alow to control the solidification processes under microgravity, without which it seems impossible to obtain significant results in the space technology for single crystal growth.

RECENT RESULTS OF MHD CONVECTION IN THE HORIZONTAL BRIDGMAN CONFIGURATION.

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The aim of this paper is to present some recent numerical and experimental results which demonstrate how a vertical uniform magnetic field is able to control (stabilize and brake) the convection in the liquid pool of a horizontal Bridgman crystal growth furnace. The numerical results, obtained for moderate values of the Hartmann number, complement a former asymptotic theory [1].

Numerics

A three-dimensionnal finite element numerical study of the M.H.D. convective flow has been developped using a modified version of the POLY3D^{TM} software available in Montreal (*Ecole Polytechnique*, UREPI). The numerical scheme is a Galerkin approximation of the Navier-Stokes equation based on the Uzawa algorithm. The vertical sidewalls of the horizontal cylinder (length / radius = 4) have fixed temperatures T1 (cold wall) and T2 (hot wall), whereas the horizontal cylindrical wall is thermally insulating. All the walls are supposed to be electrically insulating. Computations are performed within the mercury-filled cylinder for a Grashoff number of 3400 and for a Hartmann number, Ha, varying from 0 to 50.6. We find a typical M.H.D. organisation of the flow topology with a core, Hartmann layers, and shear side layers.

But the core appears to have a rather complex structure, involving two secondary vortices, symmetric from each other and centered on the cell axis. The position of the eye of each vortex is drawn nearer and nearer of the end walls when Ha increases. Therefore, the magnetic field results in the same time, in establishing a one-directionnal flow in the middle part of the cavity, and, surprisingly, in yielding a 3D flow pattern in the recirculating end regions. This last characteristics involves the emergence of an axial component of the electric field in these end regions.

Experiments

A new generation of the MASCOT (**M**Agnetic **S**tabilisation of **CO**nvection and **T**urbulence) experiment [2] has been carried out, involving an horizontal cylindrical cell (length / radius = 20) filled with mercury and equipped with 60 probes able to diagnostic the temperature <u>and</u> the electric potential, at the surface (via 55 fixed sensors) <u>and</u> into the fluid (via a movable probe). After our former experimental studies [2], which confirm the asymptotic theory in the middle part of the cell, our purpose is now to enforce the flow topology put in evidence by the numerical work and to get further informations on the stabilization of the flow as soon as the Hartmann number is of the order of a few units.

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THE INFLUENCE OF STATIC AND ROTATING MAGNETIC FIELDS ON METALLIC MELTS AND SEMICONDUCTOR CRYSTAL GROWTH

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Whereas static magnetic fields can be used to damp time-dependent convective flow in electrically conducting fluids, rotating magnetic fields are able to induce a controlled flow motion. This leads to a higher heat and mass transport, to a higher crystal growth velocity (in particular for the growth from metallic solution) and a more stable growth interface.

To produce a static magnetic field, a solenoid (B_{max}=500 mT) with an inner diameter of 220 mm was available. A 3-phase stator with an inner diameter of 138 mm was used to obtain a rotating magnetic field of B_{max}=29.0 mT, at a rotation frequency of 50 Hz. In the core of the solenoid, a 3-zone resistivity furnace was mounted (inner diameter: 30 mm, outer diameter: 100 mm, T_{max}=1200°C). The heater was controlled by an OFT-system (optical fiber thermometry) using sapphire sensors as light-pipes. A monoellipsoid mirror furnace was used to perform silicon crystal growth experiments in the static magnetic field.

The convective temperature fluctuations in liquid gallium at 850°C, caused by buoyancy convection, have been measured directly in the melt and compared with the temperature fluctuations by overlayed forced convection due to the rotating magnetic field. Without magnetic field, the temperature fluctuated about 1-2°C with frequencies in the range of 0.05 to 0.15 Hz. Under 5.6 mT, the temperature fluctuations decreased to $\Delta T<0.1$°C, showing a main frequency of 1.1 Hz. Under 10.0 mT, fluctuations of $\Delta T \approx 0.05$°C and a main frequency of f=2.1 Hz have been measured. Using the formula given by BRÜCKNER AND SCHWERDTFEGER[1], a maximum flow velocity of v=38 cm/s is reached with a magnetic induction of 29.0 mT and 50 Hz. The axial temperature gradient in the melt is decreased by a factor of 2, due to the higher convective heat transport.

In the static magnetic field, the transition from time-dependent flow to periodic flow and to laminar fluid motion has been measured in dependence on the Rayleigh- and the Hartman-number.

The effect of the static magnetic field on the dopant segregation in floating-zone grown silicon and the influence of the rotating magnetic field on the micro- and macrosegregation of Ge:Ga crystals will be given.

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PECULIARITIES OF FLOW AND HEAT AND MASS TRANSFER IN CRYSTALLIZING MELT UNDER ACTION OF MAGNETIC FIELD WITH DIFFERENT DIRECTION

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Application of magnetic field under crystalline materials production has attracted considerable attention in connection with possibility to control the melt flow velocity. However, as of experiments demonstrate, use of constant magnetic field leads to ambiguous results for quality of crystals grown in these conditions. The results of numerical calculations carried out for the case when the melt flow velocity was large and had pulsating component shown that axial magnetic field in cylindrical ampoule reduces oscillations of dopant concentration in grown crystal (microsegregation) but increases radial macrosegregation /1/.

A study of fluid flow and heat and mass transfer in crystallizing fluid under interaction between natural convection and constant magnetic field acting along the x- and y-axes and also at an angle of 45^0 to these axes had been carried out for square cavity and parallelepiped in which fluid flow on the z-axis had taken into account very approximately (psedothree-dimensional flow). The Grashof number was chosen from $2 \cdot 10^6$ to $2 \cdot 10^7$ under the Prandtl and Schmidt numbers are given 0.018 and 10 respectively. Action of the Lorentz force on the fluid was decribed in uninduced approximation.

In the field of small magnetic intensity (up to the Hartmann numbers are equal ~ 200) oscillations of all parameters (velocity, temperature, dopant concentration) disappear but transverse difference of dopant concentration on phase boundary behaves by unalike manner under different orientation of magnetic field. There are both local minima and local maxima of dopant nonhomogeneity. Thus, the ambiguity of experimental results obtained in this field are attributable to peculiarities of melt flow under different orientation of magnetic field about buoyance force and phase boundary.

In the field of intervening values of magnetic intensity (the Hartmann numbers between 200 ana 5000) there is sharp increase of dopant nonhomogeneity with maximum in the area of 4500.

In the field of the great magnetic intensity (the Hartmann numbers between 5000 and 20000) melt flow continues to die down and dopant nonhomogeneity on phase boundary is reduced. However, in the case when magnetic field is aligned with buoyance force the specifical flow is formed nearby heating and cooling surfaces, for example close by crystallization boundary. This flow is damped out very slowly with increase in magnetic intensity.

Basic facts obtained for rectangular area had been confirmed by calculations carried out for cylindrical ampoule with axial magnetic field.

Qualitative correlations with the experimental results /2,3/ lend support to the validity of used calculated method.

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THERMOCAPILLARY CONVECTION IN TWO-LAYER SYSTEMS AND CRYSTALLIZATION OF ONE OF LAYERS UNDER ACTION OF CONSTANT MAGNETIC FIELD

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Two-layer fluid systems are a very interesting matter for study of theoretical hydromechanics problems and first of all stability of shifting flows /1/. For practical applications of most fundamental importance is an use of these systems under monocrystal production. Possibilities which are caused by use of supplementary fluid layer to bases crystallizing fluid were first noted in /2,3/ where it was shown that selection of suitable fluid pairs can trade off a very substantial rise of dopant homogeneity of growing crystals. Specifecal peculiarity of two-layer systems is also extensive domain of oscillatory regimes in space of twelve dimensionless parameters.

Complicated structures of flows in two-layer systems and an availability of different oscillatory regimes poses problem to provide a high accuracy of finite difference scheme and stability of computer algorithm. The used finite difference scheme had been constructed on the five-point mold with a conditionally monotonic approximation of convective terms in the Navier-Stokes equations. The scheme possesses also the conservative properties and has the third order of accuracy.

The action of constant magnetic field on fluid had been described in uninducted approximation. Three additional dimensionless parameters (the two Hartmann numbers and ratio of conductances of fluid layers) to twelve others allows to increase possibilities for practical realization of crystal growth by two-layer technique.

The calculations were shown that the variations of values and direction of magnetic field can effect on flow and heat and mass transfer in the same manner as an arbitrary choice of physical properties of fluids. The small magnetic fields allow to lower the parameters oscillations in unstable regimes of thermocapillary convection .

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MHD MEANS TO CONTROL THE PROCESSES OF TRANSFER IN SPACE TECHNOLOGIES FOR SINGLE CRYSTAL GROWTH

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Employing of different types of electromagnetic fields (EMF) in processes of space technologies is of a great interest as from the point of view of modeling of hydrodynamic and heat/mass transfer processes on the ground in situations similar to those occurring in space as for an active and purposeful control of heat/mass transfer processes just under microgravity [1,2].

The goal of the present paper is to demonstrate (accounting for some examples) the advantages of MHD means of transfer processes control in space technologies for semiconductor single crystal growth, to analyze the effect of possible additional actions caused by the above means and to correlate results of the studies obtained in space for single crystal growth with the results obtained on the ground by MHD modeling methods.

In particular, the paper discusses the problems of the magnetic field employment as means to stabilize and suppress residual convective flows of a gravity and non-gravity character. Here one can find the data on the steady magnetic field effects on hydrodynamics and heat/mass transfer in the melt as well as some simple criterial dependencies to estimate the above field effects on the thermogravity and thermocapillary convections are proposed. A possibility of generation of specific additional types of melt convective flows in steady magnetic fields is analyzed here, too. The example of the thermoelectromagnetic convection illustrates the action of the above fields on characteristics of the growth process.

The features of the alternating field action on hydrodynamics and heat/mass transfer in the melt and at the solidification front are also discussed. A rotating magnetic field serves there as an example of the alternating magnetic field employment for: flow stabilization, stirring of multi-component melts, change of the solidification front shape, etc.

A combination of two types of magnetic fields in one electromagnetic device is proposed in order to control the growth processes by the combined field effect as well as to develop optimal regimes of single crystal production in space for their henceforth realization under the ground conditions.

It is much simpler to obtain optimal conditions for semiconductor single crystal growth by the electromagnetic fields under microgravity than on the ground. Therefore, it is purposeful to use orbital flights to prove principal possibilities of perfect single crystal production under the above conditions, and development and perfection of the parameters of electromagnetic effects on the ground processes. The data obtained should serve as a base for creation of similar conditions and technologies on the ground.

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FEATURES OF BULK SINGLE CRYSTAL GROWTH UNDER ELECTROMAGNETIC EFFECT ON MELT

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Electromagnetic action by steady and alternating magnetic fields is one of effective means to control hydrodynamics and heat/mass transfer in the process of single crystal production from melts.

The present paper is dedicated to physical and numerical simulation of the effect of axially-symmetrical steady and alternating magnetic fields on melt hydrodynamics at the Czochralski single crystal growth. It also describes some peculiarities of the growth process and characteristics of single crystals (germanium, silicon) obtained.

It is shown that some magnetohydrodynamic phenomena (causing transformation of the flow velocity pattern, for example, appearance of specific MHD boundary layers at the solidification line) can strongly affect hydrodynamics alongside with the classic phanomena of suppression of the averaged flow velocity and its oscillating components in steady uniform magnetic fields.

In order to make distribution of impurities and dopants along the crystal diameter more uniform, the method employing the effect of an axial nonuniform magnetic field has been used. Theoretically and experimentally it has been shown that in the case, when the magnetic field induction is minimal at the solidification line and maximal near the crucible's walls and bottom (an axial-radial magnetic field), the subcrystal swirl lies in the vicinity of the solidification line, but the meridional flow (connected with the free and thermocapillary convections) is being moved from the crucible walls into the zone of a weak magnetic field near the solodification line. Thus, the axial-radial magnetic field actively suppresses the averaged flow and oscillations of velocity, temperature and concentration in near-wall zones, but it does not stop the melt stirring in the subcrystal zone. Obviously, the discussed phenomenon can be used for an active oxygen concentration control in silicon single crystals.

The physical and mathematical modeling of the CZ single crystal growth in an axial alternating magnetic fields proves the possibility to intensify melt stirring as well as to control melt flow pattern and to significantly decrease temperature gradients in real growth processes, etc. Study of the silicon and germanium single crystals grown in an alternating magnetic field showed that in this case it was possible to grow single crystals with a 1-3% radial uniformity of dopant and impurity distribution at a higher micro-uniformity of their distribution along the crystal axis and diameter. Hence, the effect of an alternating magnetic field can be employed at production of high quality materials including those with a low critical tension of dislocation occurrence, such as ArGa, when the growth process is being conducted at small temperature gradients.

As the experiments show, the methods discussed allow to obtain single crystals of high purity by decreasing content of impurities supplying from containers due to the skull formation on the container's bottom and side walls.

THERMOELECTROMAGNETIC CONVECTION IN PROCESSES OF BULK SINGLE CRYSTAL GROWTH IN A STEADY MAGNETIC FIELD

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It is doubtless now that the thermoelectromagnetic convection (TEMC) induced in melts as a result of thermal current interaction with an external magnetic field, significantly affects hydrodynamics and heat/mass transfer in solidification processes of metals and alloys conducted under the action of steady magnetic fields. The most strongly TEMC affects the melt hydrodynamics in the processes of semiconductor single crystal growth, in which the thermo-e.m.f coefficients α are known to be large enough as for the liquid as for the solid phases.

The first works on the subject [1,2] paid much attention to TEMC appearance as a result of the melt contact with conducting walls of a container (crucible). But the similar TEMC appearance at the solid-liquid interface in the solidification process has not been thoroughly studied. In [1] it has been suggested that possible reasons of the thermal current occurrence at the interface should be melt possible overcooling as well as non-unifromity of the thermo-e.m.f coefficients α distribution at non-uniform distribution of dopants and impurities, the facet effect, thermal deformations in a solid phase, etc.

The main goal of the present paper is theoretical and experimental study of the above phenomena including TEMC occurrence in a liquid phase and at the interface with regard to the main methods of single crystal growth (Czochralski and Bridgman). The paper discusses two theoretical models of the TEMC occurrence. The first one assumes non-isothermality of the interface, and the effects occurring at crystal growth from a conducting crucible are modelled [2]. The second model assumes the isothermality of the interface and existence of dependency of a on temperature and admixture concentration. The latter model is used to calculate the TEMC in the liquid phase, for example, at the contact of the melt with a growing crystal. The investigation of the problem has been based on numerical solution of the Navier–Stokes system of equations, the equations describing heat transfer in liquid and solid phases, equations for electrical field components, etc.

The theoretical results have been tested on semiconductor melts (Ge, InSb) and on low-temperature melts (Ga, InGaSn). A special technique of tracers has been used, the one developed for high-temperature and aggressive melts including semiconductor ones. The tracer paths have been video recorded and analyzed by a PC. In the experiments with Ga and InGaSn the flows on the melt surface have been visualized.

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STUDY OF THE THERMOCAPILLARY CONVECTION IN SEMICONDUCTOR MELTS

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The importance of the thermocapillary convection has been found first during some technological experiments in space under reduced gravity conditions. It arose a considerable interest to its study, mainly its application under weightlessness conditions, when micro accelerations are of $10^{-2}-10^{-5}g_0$ (g_0 is the free fall acceleration), as well as under conditions of the reduced thermogravity convection. Here, the thermocapillary convection can determine practically melt hydrodynamics in some experiments, particularly in crystal growth experiments.

The thermocapillary convection up to recent times was ignored at study of most tehcnological processes under earth conditions.. But, as the results show, there is a number of processes, where it should be accounted for under the earth conditions as well [1], including the processes of single crystal growth, some processes in chemical technology, vacuum metallurgy, etc.

It should be noted that at the study of the thermocapillary convection in semiconductor melts under conditions similar to those of single ctystal growth there does not arise the problem of the surface purity. In this case the necessary purity of the melt surface to study the thermocapillary convection is obtained by technical requirements for single crystal growth.

The present paper describes the thermocapillary convection study in a semiconductor melt – germanium. The screening experiments show that in germanium melt the thermocapillary convection dominates over the thermogravity one in a wide range of the melt height change **H** < 15–20 mm. And at **H** = 5 mm the ratio of the velocity of the thermogravity convection to the velocity of thermocapillary convection is $\mathbf{u}_g/\mathbf{u}_c \approx 5\cdot10^{-2}$. The experiments had been conducted on the experimental (test) bed based on the facility for single crystal growth and equipped with a device generating a vertical magnetic field. The experiments had been carried out for a number of height **H** values (5–30 mm) at the experimental container diameter **D** = 150 mm and radial temperature drop $\Delta \mathbf{T}$ = 10-20 ^{0}K. The magnetic field varies – 0 < **B** < 0.2 T. The tracer method had been employed to measure the velocity of the thermocapillary convection. The essence of the methos is the following: on a preliminary refined thermocapillary surface of the melt there fractions–tracers were supplied; their motion paths being video recorded and later analyzed by the PC. Alongside, the temperature field in the melt had been measured.

The experimental investigations prove the correctness of the presented esteems as well as they emphasize the fact that the thermocapillary convection should be accounted for in the processes of single crystal growth under the ground conditions for the Czochralski method as well.

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THE CAPILLARY PHENOMENA IN CODUCTING EMULSIONS IN THE CROSSED ELECTRIC AND MAGNETIC FIELDS IN WEIGHTLESSNESS

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Determining forces acting on the disperse particles (drops, bubbles) of the conducting emulsion in the weightlessness (by $\nabla T = 0$) are: surface tension forces; electrophoresis forces in the external electric field; magnetic forces and forces of crossed electric and magnetic field (CEMF).

In the present paper sum up is presented of experimental researches of the capillary phenomena and masstransfer in weak-dispersioness conducting emulsions in cases when these emulsions change their state when $\gamma = 1$ into the state when $\gamma = 10^{-4} - 10^{-6}$ (quasiweightlessness), in presence of external volume electromagnetic forces (VEMF) $\vec{F} = \vec{j} \times \vec{B}$.

1. When F = 0 (j = 0, B = 0) the following phenomena in the emulsions are observed: - liquid-metal drops (LMD) and bubbles capillary barbotage into bearing liquid and their capillary oscillations in forward motion; - circulation convenction streams inside LMD and in bearing under the influence of capillary forces; - capillary reflections of LMD from boundary division of bearing liquid-gas and LMD from of bubbles gas; - reducing degree of coagulation of the desperse particles, that is emulsion stability increases in weightlessness; - unpredictable drops and bubbles motion in the presence of oxides, surface-active substances and others on the boundary deivisions.

2. The following phenomena in the presence of $B \neq 0$ $(j = 0)$ in emulsions are observed; - dempfing of capillary oscillations drops and bubbles; - velocities motion LMD and bubbles decrease in magnetic field; - decrease of velocities of convenction streams in LMD and in bearing liquids.

3. The following phenomena in the presence of $j \neq 0$ $(B = 0)$ in emulsions are observed: - electrophoresical motion of LMD; - decrease of surface tension of the boundary of liquid-metal and bearing liquid (electrolyte); - decrease of LMD velocity in bearing liquid in external electric field.

4. The following conditions are created in the presence of $F = j \times B \neq 0$ in conducting emulsions: - control of capillary barbotage bubbles and LMD (facilitation of bubbles barbotage conditions allows to receive foam metal and LMD-matrix systems); - control of LMD and bubbles motion velocities in bearing liquid (separation effects in VEMF field); - appearance of surface waves of the surface of bearing liquid of LMD; - capillary oscillation of menisca bearing liquids in different directions VEMF field; - capillary reflections of LMD from of division boundaries of bearing liquid-gas in VEMF field.

EFFECT OF INDUCTOR SHAPE ON THE SHAPE OF INTERFACES AND MELT CONVECTION IN FLOATING ZONE SILICON CRYSTAL GROWTH

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Introduction. The float zone (FZ) method is often used for the growth of the silicon single crystals of large diameters (> 100 mm). The electric current is induced to melt the feed rod, which is pulled from above. The molten silicon forms the liquid zone with the free surface and crystalizes at the growing interface. The interface shapes are strongly coupled with the distribution of the EM field, and as a consequence with the shape of the inductor. The quality of the growing crystal depends on the shape of the growth interface, the temperature gradients and on the fluid flow near this interface. As it is very difficult to investigate and develop the FZ method experimentally, numerical simulation is necessary.

The main objectives of this numerical investigation is to study the interface shape and the flow velocity field depending on the inductor design and to find the limits of the process.

Mathematical model and numerical methods. The system is assumed to be axisymmetric. Due to its high frequency (2-3 MHz) the electric current flows only through a very thin skinlayer on the conducting surfaces. Therefore the Boundary Element Method is applied for the calculation of the EM field. The calculated distribution of currents is used to obtain the Joulean sources, which determine the temperature distribution, and to obtain the EM-forces which influence the free surface of the melt.

The temperature field is calculated by Finite Element Method taking into account the temperature-dependent thermal conductivity as well as the vertical movement of the crystal and the feed rod.

The shape of the free surface is determined under consideration of the gravity, the surface tension and the EM-forces. The melting and growing interfaces are calculated according to the balance of the heat flow.

For the calculation of the melt convection the EM-, buoyancy, thermocapillary and centrifugal forces are considered. The time-dependent Navier-Stokes and temperature equations are solved simultaneously using the Finite Element Method.

The coupled EM-thermal-hydrodynamic problem is solved iteratively. The mathematical model and the numerical methods are described in details in [1].

Results of calculations. The program developed allows to investigate the influence of many parameters on the shape of interfaces, the limits of the process and the stability of the floating zone as well. The influence of the inductor design on the shape of interfaces and the melt motion are demonstrated for various growth parameters. An inductor of industrial design has been taken as a basis for the investigations. Such parameters as the thickness of the inductor and the diameter of the central hole are changed. The possibility of the process, the maximal temperature difference in the melt, the curvature of the growth interface and the current distribution on the free surface are analysed.

Applying the obtained shapes of interfaces the fluid flow in the melt is calculated. Considering all the driving forces in a typical configuration used in praxis the unsteady solution for the fluid flow is obtained. The parameter area of the unstable flow is determined. The flow velocity and the intensity of velocity oscillations increase with the increasing of the crystal diameter, the temperature difference in the melt, the curvature of the growth interface and the growth rate. The meridional flow velocity decreases with an increasing rotation rate of the crystal.

The analysis of the influence of various parameters will be used to optimize the shape of the inductor and to find a set of optimal growth parameters in order to improve the crystal properties.

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Convection

A METHOD OF PARAMETRIC APPROXIMATIONS FOR LAMINAR MHD THERMAL BOUNDARY LAYER AROUND A DEFORMABLE BODY

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The unsteady laminar magnetohydrodynamic (MHD) thermal boundary layer on a deformable body in a non uniform motion : U (x,t) = $\Omega(t).V(x,t)$ in the presence of some given magnetic field is discussed. The analysis includes the case of low temperature differences with constant fluide properties ρ and μ (i.e. independent of temperature). Then the velocity field is independent of the temperature field so that the two flow equations can be solved first and the result can be employed to evaluate the temperature field.

A universalisation of both - dynamic and thermal boundary layer equations - is first made in the sense of Loitsianskii, i.e. that neither equations nor boundary conditions depend on particular problem data. The universality is ashieved by introducing a new normal variable ($\eta = Ay/\delta_p$) and by transfering sets of parameters which express the influence of time and deformability conditions :

$$\left.\begin{aligned} g_k &= \frac{1}{\Omega}\frac{d^k\Omega}{dt^k} Z_p^k \\ p_k^n &= \Omega^n V^{n-1} \frac{\delta^{k+n}V}{\delta x^n \delta t^k} Z_p^{k+n} \\ \gamma_k^n &= \Omega^k V^{k-1} \frac{\delta^{k+n}V}{\delta x^k \delta t^n} Z_p^{k+n} \end{aligned}\right\} \quad k\in(1,2,.....) \text{ et } n \in (0,1,....)$$

as well as of the given magnetic induction : $\beta_1 = N.Z_p$, characteristic for each particular problem, into the new variables. Here x denotes the distance along the surface of the contour from the forward stagnation point, y - the normal distance to the surface, t - time, μ - the fluid viscosity, ρ - the fluid density, B - the applied transverse magnetic flield, σ - the electrical fluid conductivity, $\delta_p(t)$ - the displacement thickness of the MHD boudary layer on the flat plate, N = ($\sigma.B^2 / \rho$) - the magnetic parameter.

Subsequently, the solutions of the obtained universal equations, of both - dynamic and thermal boundary layers - are found in the form of series expansions in mentioned parameters.

Finally, an application of the proposed method is done by calculating the boundary layer on a circular cylinder whose radius R (initial value Ro) grows in time with a constant acceleration a : R = Ro (1+at), started at the same time impulsively with a uniform velocity U_∞ along a rectilinear path in a conductive fluid initialy at rest, in the presence of an external transverse magnetic field of the constant induction B. So we obtain, for instance, that the dimensionless distance of first boundary layer separation s, appearing in a point on a cylinder defined by angle θ, is presented by :

$$1 + \alpha\, s + (1/2)\,[\,1 - \exp(-\,(4/3)\,\dot{N}\, s\,)]\,(1+\alpha\, s) + (1/\dot{N})\,(\,(\,(3\pi+4)/\pi)\,\cos\theta - (3/2)\,\alpha\,\theta\,\mathrm{ctg}\theta\,) = 0,$$

where $\dot{N} = NRo/U_\infty$ denotes the magnetic Stuart number, and $\alpha = (aRo)/ U_\infty$ designates the quotient of two speeds - this of deformation of the cylinder dR/dt and that at infinity upstream U_∞.

From there the detailed numerical analysis gives that , even in the case of non conductive fluid flow ($\dot{N} = 0$), the distance s of the first boundary layer separation increases with the augmentation of the parameter α. Applying an external magnetic field, this distance s increases progressively, all the more as the Stuart's number N is biger. This fact could be useful for the technical practice.

TESTING OF A NEW EXPERIMENTAL TECHNIQUE TO STUDY MHD-ASSOCIATED PHENOMENA WITH FREE LIQUID METAL SURFACE

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The technique is based on creating juvenile surface of liquid metal in a finite volume container with insufficient amount of active gas molecules to form a film on the surface of the liquid metal. For the first tests stainless steel container with a hermetically closed glass lid were produced and evacuated to residual gas pressure of 10-3 Pa and then filled to 2 mm depth by a layer of liquid Gallium. The juvenile surface of liquid gallium acted as a getter of residual gas, but the relation of amount of gas atoms to Gallium atoms, forming the juvenile surface, being << 1, the liquid metal surface remained free. The quality of liquid Gallium free surface did not detectably deteriorate during six months after production.

A temperature drop of 100 K along 2 cm of container radius R was applied at the conducting bottom of the container with an aim to detect the thermocapillary covection. A slow motion, with maximum velocity up to 3 mm/s, was observed. In these first tests the free surface properties and Marangoni number Ma remained unknown up to the value of order, but the presence of thermocapillary convection was proved by the observed flow direction on surface opposite to thermogravitational one.

Applying steady axisymmetric magnetic field B, while the bottom and side walls of the container were conducting (stainless steel), led to intensive convection in Gallium due to B interaction with thermoelectric currents. At the azimuthal rotation rate due to this interaction of 6 rad/s, the centrifugally driven meridional convection may have been more intensive than thermal convection, leading to substantially increased convective heat transfer.

The melting of gallium was observed, while the center of the container bottom was heated and the rim cooled. The melting rate oscillations were observed, which started at given critical heat flow density through the melting front. It seemed, that even negative melting rate - recrystallization - occurred.

During melting of Gallium in presence of magnetic field and, consequently, thermoelectromagnetically driven melt rotation, oscillations of melting front were not observed. Stabilization of melting rate may be considered in terms of increased convective heat transfer due to centrifugally driven meridional convection, not allowing the liquid phase undercooling in vicinity of the melting front.

NATURAL CONVECTION IN RECTANGULAR ENCLOSURES OF ARBITRARY ORIENTATION WITH VERTICAL MAGNETIC FIELD

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In recent years there has been much interest in the effect of electromagnetic forces on natural convection when the fluid is electrically conducting and a magnetic field is present. Considerable success has been achieved with analytical solutions for situations where motion is damped to such an extent that the temperature field is approximately that due to pure thermal conduction. Several numerical studies have been undertaken to elucidate behaviour when motion is strong enough to distort the temperature field, but it seems that there has been little attempt at asymptotic solution of the other condition which might be susceptible to analysis, namely that of dominant advection of the temperature field. The aim of the present paper is to treat a situation which is simple enough to yield to asymptotic analysis for both ends of the advection scale, negligible and dominant, while retaining enough geometrical complexity to be non-trivial. It is hoped that the results may prove useful as a check of more extensive computational investigations.

A two-dimensional flow field is taken to be bounded by two parallel, thermally insulating planes, and at right angles to them are two parallel planes carrying uniform heat flux to and from the resulting enclosure. A uniform magnetic field is applied vertically and it is assumed that electric current can flow freely in a direction perpendicular to the flow plane. Viscous and inertia forces are taken to be negligible except in thin layers. Behaviour is then found to depend on the parameter Ra/Ha^2, where Ra is the Rayleigh number and Ha the Hartmann number. The combination is a measure of the ratio of possible buoyancy forces to electromagnetic.

When $Ra/Ha^2 \to 0$, thermal advection dominates over conduction and a major part of the flow field consists of a pure shear flow parallel to two of the bounding planes; whether they are the thermally insulating ones or those carrying uniform heat flux depends on the orientation of the enclosure. Streamlines returning the flow in regions adjacent to the other two planes form rectangular hyperbolae.

When $Ra/Ha^2 \to \infty$, the dominance of the temperature advection forces isothermals to be horizontal in a 'core' and motion there is negligible. Flow is confined to novel thin layers on the bounding planes, the thickness of the layers being of order $Ha/Ra^{1/2}$. Since it is assumed that Hartmann layers exist on a much smaller scale, the Rayleigh number must be ordered so as to give $Ha^4 >> Ra >> Ha^2$. Since the motion is limited, the Nusselt number takes a value which is of order unity, i.e. comparable to that for $Ra/Ha^2 \to 0$.

Difficulties arise in the analysis for $Ra/Ha^2 \to \infty$ when the bounding planes with uniform heat flux are vertical and also when the constant-heat-flux condition is replaced by one of constant temperature. Some qualitative discussion is made possible by acknowledging that a novel free layer, aligned with the horizontal direction and of thickness order $Ha^{1/2}/Ra^{1/4}$ may separate regions of different horizontal velocity and vertical temperature gradient.

LOCAL CHARACTERISTICS OF THERMAL BOUNDARY LAYER IN A MODEL OF ELECTROSLAG FURNACE WITH AXIAL CURRENT SUPPLY

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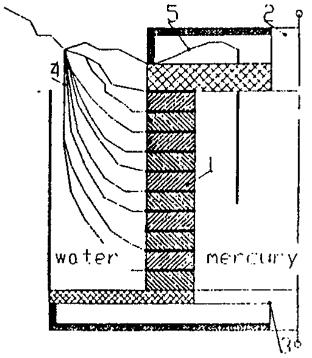
For electrometallurgical aggregates important aim is the determination of heat conditions in the nelt. The presence of internal heat sources and melt complex convection structure in the lectrometallurgical furnaces create different conditions for heat transfer at the different parts of rystallizer. In this report experimental results, devoted to distribution of local heat resistance of oundary layer on the crystallizer wall, which were obtained on the mercury model of electroslag urnace with single phase current supply, are presented.



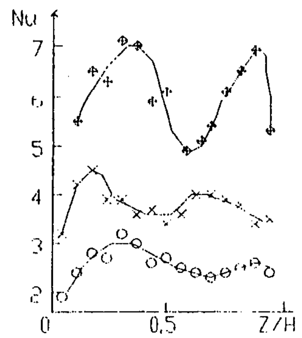


Fig.2.Nuselt number distribution along the side wall of the mercury bath:
$S = 7{,}5\cdot 10^9\ d/D = 0{,}2(\otimes)\ 0{,}6(\times)$
$S = 3{,}3\cdot 10^9\ d/D = 0{,}2(o)$
$Nu = (T_2' - T_0')/(T_{1.2}' - T_2')$

Fig.1. Physical model of electroslag furnace.

Physical model construction is shown at the fig.1. Mercury bath is placed in the body 1 (H/D=0,7; D=100) which consist of 10 separated steel rings. Due to electrical current between lectrodes 2 and 3 intensive mercury convection and Joule heat release exist in the bath. Side wall of he model is placed in the constant-temperature reservoir with cooling water. Temperature neasurements in the mercury bath were provided by the thermocouple 5, but in the wall, by using riginal method for measuring temperature difference between the internal ($T_{1,2}'$) and external (T_0') urfaces for each of the rings independently.

Mercury flow in experiments had a developed turbulent character. More then 60% of it ccupies the constant temperature (T_2') **heat core.** Maximum of the temperature was observed only n the small area under the smaller electrode ($T_{max}' = (1{,}5...2{,}0)T_2'$). All temperature gradients are oncentrated in boundary layer near the wall. It's characteristic dimension approximately equals),1...0.15R. Distribution of boundary layer heat resistance (see fig.2) is close related with the tructure of the convection. Existing of large scale eddies in the flow stimulate heat transfer between he wall and liquid. This fact opens the wide spectrum of possibilities to control heat situation in the ath of electroslag furnace.

NUMERICAL COMPUTATION OF DOUBLE DIFFUSIVE NATURAL CONVECTION OF LOW PRANDTL NUMBER FLUID IN A RECTANGULAR BOX

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The double diffusive natural convection occurs when density changes are caused by both concentration and temperature gradients. Natural convection of a low Prandtl number fluid in a rectangle with combined horizontal temperature and concentration gradients was carried out numerically. These phenomena may become important to study the problems of engineering with the double diffusive phenomena such as crystal growth processes, casting of metal alloys, etc.

The boundary conditions at the vertical side walls were imposed in such a way that one side wall is hot in temperature and low in concentration and reversely the other wall is cold and high. Namely the flow pattern of thermal and solutal buoyancy forces near the walls are the cooperating case. A Galerkin finite element method was employed for the numerical analyses of this double diffusive convection. Two-dimensional system was presumed. The basic equations consist of the stream-function equation, the vorticity equation, the energy equation and the concentration equation. The unequal triangular elements were employed with the smaller ones near the walls. Computations were carried out for the Prandtl number Pr=0.01, the Lewis number Le=100, the aspect ratio A=2, the Rayleigh number Ra=10^4 and buoyancy ratio (= solutal buoyancy / thermal buoyancy) N= 3, 10 or 20 .

The detailed pattern of the flow was studied for different buoyancy ratios. In the case of N=3 a large roll cell in which the concentration was uniform was formed at first but tended to become gradually round. Next two secondary small roll cells which have a circulation in opposite direction, compared with the main roll cell, were formed under the surface and above the bottom respectively. Then the interface between roll cells have concentration gradients. This is the typical double diffusive convection but the direction of flows both above and below an interface are the same differently from the case of normal Prandtl number fluids. In the case of N=10 a large roll cell was formed at first but a fluid of high or low concentration flew into the main roll cell and then the secondary roll cells were formed occasionally in the main roll cell. Then the boundary of the roll cell had concentration gradients. In the case of N=20 a large roll cell was formed at first but a fluid of high or low concentration flew into the main roll cell and then the secondary roll cells were formed in the main roll cells. However the main roll cell changed to the concentration stratified layer with time and two small strong roll cells developed under the surface and above the bottom. The oscillatory phenomena of flows occurred at N=10 and 20 but little at N=3.

FREE THERMAL MHD CONVECTION NEAR VERTICAL PLATE AND ABOVE LINEAR HORIZONTAL HEAT SOURCE WITH SMALL PRANDTL NUMBERS

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The stationar free thermal MHD convection near vertical plate and above linear horizontal heat source with small Prandtl numbers Pr and large Lykoudis numbers $Ly = 2Ha^2/\sqrt{Gr}$ (Ha- Hartmann number, Gr- Grashof number) are examined. The external magnetic fields have the following form (the x axis is vertical, the y axis is horizontal)

$\vec{B^e} = B_o(L/x)^{1/4}\vec{e_y}$ - for the plate (1)

$\vec{B^e} = B_o(L/x)^{2/5}\vec{e_y}$ -for the line heat source. (2)

Boundary layer and inductionless approximations, that makes magnetic field (1) and (2) to leave the corresponding problem self-similar are used. The exact asymptotic solutions of both problems where obtained using the matched asymptotic expansions method with $\Pr \to 0$. When the magnetic field is abcent (Ly=0) then the expansions of heat flux by $\sqrt{\Pr}$ coincides the expansion, obtained earlier in [1]. Moreover, the exact numerical solutions of these problems until Ly=50 where obtained. If $\Pr \le 0.01$ the asymptotic solution practically coincides the exact numerical solution when $Ly \ge 10$. The asymptotic of the vertical component of velocity v on the axis y=0 of the linear horisontal heat source (when $\Pr \to 0$ *and* $Ly \to \infty$) are obtained in the form:

$$v = 2(Ly + \sqrt{Ly^2 + 3.2})^{-1}. \quad (3)$$

In the following Table the meanings of velocity v when Pr=0.01 are shown. First line in the Table shows the results of using formula (3), second shows the exact numerical solution of the problem.

Ly	1	2	5	10	25	50
$-\Theta'(0)$ *as;in;(3)*	0.65587	0.42705	0.19398	0.09921	0.03995	0.01999
$-\Theta'(0)$ *numeric.*	0.63215	0.42323	0.19378	0.09919	0.03995	0.01999

As it can be seen from this Table, the asymptotic and numerical solutions of velocity v on vertical axis practically coincides when $Ly \ge 5$ and Pr=0.01, .

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OBLIQUE HYDROTHERMAL WAVE INSTABILITY OF THERMOCAPILLARY DRIVEN CONVECTION IN A COPLANAR MAGNETIC FIELD

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The present study addresses the problem of hydrothermal wave instability of thermocapillary driven flow in a horizontal electrically conducting liquid layer heated from the side and subjected to a magnetic field coplanar to the layer. The main goal is to investigate the influence of both the strength and orientation of the magnetic field, laying in the plane of the layer, on the threshold of convective instability due to infinitesimal disturbances in the form of obliquely travelling plane waves. The critical Marangoni number and corresponding frequency, wave number and direction of propagation characterising the threshold of the instability are found numerically by making use of a modified spectral Chebishev tau-method. Calculations show that the minimal surface defined by the marginal Marangoni number as function of longitudinal and transversal wave numbers is constituted by two intersecting leaves. One of these leaves is related to the waves travelling crosswise to the basic flow, while the second one is related to the waves propagating along the basic flow. Further on these waves will be referred to as longitudinal and transversal ones, respectively. The particular feature of the basic flow under consideration is that it turns out to be at least linearly stable with respect to purely hydrodynamic disturbances. As a result of the hydrodynamic stability, the branch of transverse waves, which must merge with the branch of pure hydrodynamic instability as $Pr \to 0$, exists only down to the Prandtl number $Pr_c = 0.018$, where critical Marangoni number goes to infinity. Magnetic field influences all disturbances, except those aligned with the field. Obviously, application of however strong coplanar magnetic field, cannot ensure the critical Marangoni number higher than the lowest one related to the disturbances aligned with the magnetic field. Thus, if $Pr > Pr_c$, then there always exists fixed minimal Marangoni number for every direction of the imposed magnetic field. If the minimal Marangoni number, corresponding to a fixed direction of the magnetic field, belongs to the same branch as the critical Marangoni number for absent magnetic field (branch of longitudinal waves for small Prandtl number fluids [1]), then the limiting critical wave vector is reached continuously with increase of the magnetic field. Otherwise, if the critical Marangoni number for strong magnetic field lays on the transversal wave branch, then it is reached by a jump in the wave vector. The highest, over all directions of the wave vector, value of the critical Marangoni number is found to correspond to the purely transverse wave mode. Consequently, a maximal stabilisation of the flow can be achieved by applying the field crosswise to the basic flow. If $Pr \leq Pr_c$, and magnetic field lays within certain angle depending on the Prandtl number and corresponding to the absent transverse wave branch, then no saturation of the critical Marangoni number is reached, and it keeps increasing almost directly with the magnetic field strength.

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THREE-DIMENSIONAL NUMERICAL ANALYSES OF NATURAL CONVECTION OF LIQUID METAL IN CUBE WITH ELECTRO-CONDUCTING WALLS UNDER AN EXTERNAL MAGNETIC FIELDF EITHER IN THE X-, Y-, OR Z- DIRECTIONS

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Three-dimensional numerical analyses were carried out for natural convection of liquid metal in a cube with electro-conducting walls under an external magnetic field either in the X-,Y- or Z- directions. The system parameters are $Ra = 10^5, Pr = 0.025, Ha = 0 \sim 200$. The number of grids are 21 in all three directions of the cubic coordinate. The cube is heated from one vertical wall (X=0) and cooled from an opposing wall (X=1) both isothermally. Four other walls are thermally insulated. The resulted natural convection is along the heated and cooled vertical walls and its quasi-two dimensional circulation axis is parallel to the Y-direction. With an increase in the Hartmann number, the rate of heat transfer on the heated wall and cooled wall decreased monotonously. In comparison with our former computed results for the cube with electrically-insulating walls, the magnetic suppression effect was much stronger. On the effect of the direction of the magnetic field, the Y-directional one was most powerful in suppressing the convection. These are apparently due to the almost vanishing electric field in a liquid metal since the electric currents are all confined in the conducting walls. The X- or Z- directional magnetic suppressions were almost equivalent, although flow modes were different each other.

FREE THERMAL CONVECTION NEAR HORIZONTAL SEMIINFINITE PLATE IN STRONG MAGNETIC FIELD

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The stationar free thermal MHD convection near horizontal semiinfinite plate in the external magnetic field

$\vec{B^e} = B_o(L/x)^{3/5}$ (1)

(the x axis is vertical, the y axis is horizontal) is examined.

The plate is situated in the region $0 \le y \le \infty$. Boundary layer and inductionless approximations, that makes magnetic field (1) to leave the problem self-similar are used.

Let us introduce the stream function $\Psi(x,y)$ ($v_x = \partial\Psi/\partial y$, $v_y = -\partial\Psi/\partial x$), dimensionless temperature $\Theta = (T - T_\infty)/(T_w - T_\infty)$ and self-similar variables (see [1]):

$$\eta = 5(Gr/5)^{1/5} L^{-3/5} y/x^{2/5},\quad \Psi = 5\nu(Gr/5)^{1/5} L^{-3/5} x^{3/5} f(\eta), \qquad (2)$$

where $Gr = (\beta g L^3/\nu^2)(T_w - T_\infty)$ - Grasghof number.

Then the problem takes the following mathematical form:

$$f''' + 3ff'' - 2f'^2 - \tfrac{4}{5}P - \tfrac{1}{5}\eta\Theta - Lyf' = 0 \qquad (3)$$

$$P' = \Theta,\quad \Theta'' + 3\,\mathrm{Pr} f\Theta' = 0,\qquad ' = \partial/\partial\eta \qquad (4),(5)$$

where $Ly = Ha^2/\sqrt{Gr}$ - Lykoudis number, $Ha = B_o L\sqrt{\sigma/\rho\nu}$ - Hartmann number,Pr-Prandtl number, P - dimensionless pressure.

Boundary conditions have the following form (see[1]):

$$\eta = 0: f = f' = 1 - \Theta = 0;\quad \eta = \infty: f' = \Theta = P = 0. \qquad (6)$$

The problem (2)-(5) was solved numerically on a computer using special shooting method for Prandtl numbers Pr=0.01, 0.0625, 0.1, 1 untill Lykoudis number Ly=30. Moreover, the exact asymptotic for heat flux from the plate when $Ly \to \infty$ was obtained in the way as it was made in Lykoudis paper [2]:

$$\Theta'(0) = -0.74207(\mathrm{Pr}/Ly)^{1/3} \qquad (7)$$

If Pr=0.01 the asymptotic solution (7) practically coincide the exact numerical solution when $Ly \ge 10$.

In the following table the meanings of $\Theta'(0)$ when Pr=0.0625 (liquid potassium with temperature 200°C) are shown (in the first line the result using formula (7) is shown, in the second - exact numerical solution of the problem).

Ly	10	20	30
$-\Theta'(0)$ *as in*(7)	0.13669	0.10849	0.094776
$-\Theta'(0)$ *numeric.*	0.13262	0.10755	0.094776

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Fusion Applications

HEAT TRANSFER CONTROLLED BY MODIFICATION ON BOUNDARY CONDITIONS IN A STRONG MAGNETIC FIELD

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The heat transfer increase in turbulent liquid metal flows under strong magnetic field can be obtained by modification of boundary conditions on the insulating walls perpendicular to the field. The experiments were carried out in closed horizontal circular channel with liquid metal eutectic alloy (InGaSn) in vertical homogeneous magnetic field up to 1.5 T. The walls parallel to the magnetic field served as electrodes by means of which an electric current was passed through the liquid, and walls perpendicular to the field were insulated. The fluid was set in motion by interaction of the radial electric current and applied magnetic field. The inner and outer side electrode-walls contained the heater and cooler, respectively.

The inhomogeneity of the surface of the wall leaded to the appear of vorticity parallel to the field and generation of large-scale two-dimensional turbulent vortical structures stretched along the field. The structures were commensurable with channel cross-section and appeared as a result of flow around MHD stagnant zones forming above promoters under magnetic field due to the electric current gradient along the field on the boundary of promoters. These vortical structures provided the effective heat transfer mechanism.

The radial distributions of averaged and pulsation velocities and temperature were measured by electrical potential and thermo probes. The intensity of heat transfer from the hot wall to the flow was determined by the Nusselt-number (Nu). Experiments shown that heat transfer coefficient increases 3 times at the strong magnetic field in both cases of flow promotion compared with the case of free channel flow (without promoters), where the turbulence was small-scaled.

The Nu-Rh dependence was received, where Rh is characterized by the ratio of inertial force and friction one on the wall perpendicular to the field. The ratio E = Nu/W introduced reflects the heat transfer efficiency, where W is the power spent to set the fluid in motion. In spite of some additional MHD losses the appear of the large two-dimensional vortices provided the intensive heat transfer, so the value E in flow with promoters was 4 times less than in free channel flow and what is more at relatively small flow rates. Thus, performed studies give one of the possibility of heat transfer control in a liquid metal flows under magnetic field in channel with insulating walls.

MHD INVESTIGATIONS FOR LIQUID METAL FUSION BLANKETS

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Self-cooled liquid metal blanket for a DEMO-fusion reactor are being developed at the Research Center Karlsruhe (FZK) as part of the European Blanket Program. A crucial issue of any blanket design is the sufficient cooling of the plasma facing first wall.

By means of simplifying correlations the particular MHD-aspects of this issue will be outlined and applied to several characteristic design concepts e.g. a poloidal-toroidal multi-channel design as well as to a purely poloidal concept and to the so called hybrid "Dual Coolant Concept" which utilizes pressurized helium for cooling the first wall and liquid metal for the other ducts.

Experimental and theoretical MHD-investigations related to relevant components of these concepts will be presented with focus on the velocity distribution, MHD turbulence and the resulting heat transfer from the first wall of liquid metal cooled blanket concepts. The corresponding experiments being conducted in close cooperation between FZK and LAS, Riga showed that for fusion relevant Ha and N a vortex structure exists in poloidal-toroidal flow concept as well as in the poloidal front channel of a purely poloidal flow concept leading to a remarkable improvement of heat transfer.
For the present blanket designs it can be shown that no MHD feasibility issues exist even under the very stringent assumptions made with respect to the heat transfer behaviour.

The results of the MHD turbulence and heat transfer experiments conducted at fusion relevant conditions show that even more simple MHD adapted flow concepts are possible if by properly chosen measures MHD turbulence occurs increasing remarkably the heat transfer from the first wall.

INTEGRAL MHD-HEAT TRANSFER BEHAVIOUR IN DUCTS WITH ELECTRICALLY INSULATED COATED WALLS

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In designing a self-cooled liquid metal fusion blanket the heat transfer from the highly heat loaded first wall plays a dominant role. If pure conduction heat transfer from the first wall to the bulk of the liquid metal is assumed steep temperature gradients would result, prohibiting simple MHD adapted flow concepts. Therefore research in heat transfer enhancement by means of MHD-turbulence is demanded, providing data for more advanced design concepts.

In a heat transfer-experiment carried out in the MEKKA-facility the side wall of a rectangular (80 mm x 40 mm) test section is heated over a length of 0.5 m using a direct contact heater, which allows a homogeneous heat flux up to 20 W/cm^2. The test section is made of stainless steel, the liquid metal contacting surfaces are electrically insulated by a temperature resisting painting. The temperature distribution of the heated sidewall is measured using 12 thermocouples fixed at the fluid/steel interface. The temperature and velocity distribution have been recorded by a combined traversable temperature/-potential gradient probe at different axial positions. Two series of heat transfer measurements have been conducted, one without, the others with 2 turbulence promoters in the form of round rods of glas fiber reinforced epoxy arranged parallel to the B-field direction at the inlet and in the mid of the test section. Hartmann Numbers up to 5000 (2 Tesla), interaction parameters 320-22000, Peclet numbers 44-2200 based on the half-width in the field direction ($a=40$ mm), and velocities of 0.04 to 2.5 m/s, have been achieved. The working fluid was NaK (sodium potassium eutectic).

The experiments showed that:

- The pressure drop without turbulence promoters (TP) is about 8 times higher than predicted for perfect insulation, after "wetting" and operation at about 150 °C.
- Due to the imperfect insulation the velocity distribution showed not a slug flow type as predicted for perfect insulation.
- Even in the case of a channel without any turbulence promoter the heat transfer is improved with respect to laminar slug flow for Peclet-numbers above 140 due to the start of a two dimensional vortex structure. For the highest Hartmann and Peclet numbers measured this increase has been by a factor 2.8 higher than predicted for laminar slug flow.
- After inserting 2 mechanical TP`s strong oscillations are observed improving the heat transfer by a factor 7 for $Pe=2200$. A cost (increased pressure drop) - benefit (improved heat transfer) analysis demonstrates the efficiency of the chosen mechanical turbulence promoters.

CONVECTIVE-DIFFUSIVE TRANSPORT IN THREE-DIMENSIONAL LAMINAR MHD FLOWS

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Liquid metals are considered as cooling media for application in fusion reactor blankets. Their high heat conductivity and the capability to act as breeding material and as excellent coolant simultaneously encourage scientific work since many years. Despite these obvious advantages several severe problems have to be overcome in order to widen the acceptance of liquid metal use within the community of fusion researchers.

During the last years the progress in magneto–hydrodynamic (MHD) research led to quite a good understanding of the flow structure and the pressure drop associated with the flow of the electrically conducting coolant within the strong, the plasma confining magnetic field. Asymptotic methods play here a key role in the analysis of complex three–dimensional (3D) flows since it is not to be expected that fully numerical simulations may lead to accurate solutions within the near future in the range of fusion relevant parameters.

In the present work the heat transfer problem in 3D MHD flows is considered. The governing equations for momentum, mass and charge conservation, and Ohms law are solved in the asymptotic limit of large Hartmann numbers *Ha* and large interaction parameters *N*. Inertia and buoyancy effects are assumed to play only a minor role since the pressure gradients caused by velocity gradients or density variations are much lower than the pressure gradient which is necessary to maintain the forced flow. Under these assumptions the momentum equation decouples from the energy equation. The latter reduces to a convective–diffusive transport equation used for the computation of the temperature which plays the role of a passive scalar.

The flow field is obtained by using a 3D code for the calculation of MHD flows in arbitrary geometries. This code takes profit from the fact that at high values of *Ha* almost the entire flow region is occupied by an inviscid core. In the core the flow is dominated by a balance between the pressure gradient and the Lorentz force. The boundary conditions at the walls are satisfied by solving viscous boundary layer equations simultaneously with the solution of the core flow. All basic equations are formulated in tensor notation. The use of boundary–fitted coordinates finally leads to a universal code which can be applied to any desired channel geometry in a transverse strong magnetic field.

The energy equation used for the calculation of the temperature field is formulated in the same tensorial notation and coordinates in order to keep the main advantages of the method described above. Diffusive fluxes are neglected with respect to the strong convective fluxes in the axial direction for high values of the Peclet number *Pe*. This assumption allows an efficient explicit formulation in the axial direction while the diffusive and convective fluxes in the transverse direction are treated by a fully implicit scheme. Results are compared with known exact solutions or with solutions obtained for very special geometries by other numerical approaches. The agreement for all cases considered is good and shows sufficient accuracy for engineering applications.

HEAT TRANSFER EXPERIMENTS IN A TURBULENT SODIUM MHD CHANNEL FLOW

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The transfer of heat and ist transport as a passive scalar in turbulent flows is known as one of the standard problems in Hydrodynamics. Because of technological applications, for instance associated with crystal growth techniques or the liquid metal blanket cooling concept of nuclear fusion reactors, growing interest exists in the understanding and use of magnetic field control of these transport phenomena.

Exposing the flow of a conducting fluid to an external magnetic field creates a special type of turbulence, which is unknown in ordinary hydrodynamic engineering. While the structure of turbulent MHD flows has already been investigated very intensively, the understanding of the transport properties of the MHD turbulence is still on the beginning. Due to the presence of the magnetic field the vorticity is almost aligned with the direction of the field lines. Thus, two-dimensional vortices arise, which are scarcely affected by the electromagnetic forces.

Our experimental effort is directed to the following question:

Is it possible to enhance the heat transfer perpendicular to the direction of the magnetic field as a result from a well-aimed promotion of the anisotropic properties of the MHD turbulence ?

For this purpose we extended our sodium loop with a new horizontal test section for heat transfer measurements. Constructive solutions have been realized, which guarantee a high level of flexibility concerning the experimental configuration. So, it is possible to add honeycombs, grids, mechanical turbulence promoters or wall inserts (in order to modify the wall conductance ratio) to the interior of the test section. The heat will be produced by an electrical heater connected via a copper plate with the channel wall parallel to the magnetic field. At first our measurements will be focused on the Nusselt number depending on the flow configuration as well as the intensity of the magnetic field. The whole test section is equipped with thermocouples (partially moveable installed). Measurements of the liquid velocity including their fluctuations in flow direction are possible by means of potential probes.

In frame of this paper we will present first results obtained for the simplest experimental configuration without any inserts in the test channel.

MEASUREMENTS OF LONGITUDINAL VELOCITY FLUCTUATIONS IN LIQUID SODIUM AT HIGH INTERACTION PARAMETRS IN A CHANNEL WITH CONDUCTING WALLS

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The intensity of MHD turbulence can be enhanced by mechanical inserts such as cylinders or grids. Because of the two-dimensional character of the turbulent flow in the presence of a magnetic field the orientation of the rods with respect to the field direction is essential. Vortices will be scarcely damped over long distances if their axes are aligned with the field lines.

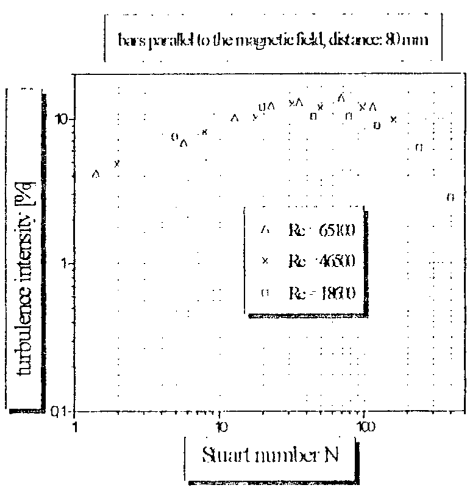
The decay of the turbulent fluctuations is clearly affected by the conductivity of the walls. High conducting walls (for example Cu) support the closure of the induced currents and by this the prompt damping of the turbulence, while in a flow bounded by nonconducting walls two-dimensional fluctuations with a long life time can be observed. Both cases have already been investigated intensively. The situation of the standard technological case with channel walls made of stainless steel is the subject of this paper.

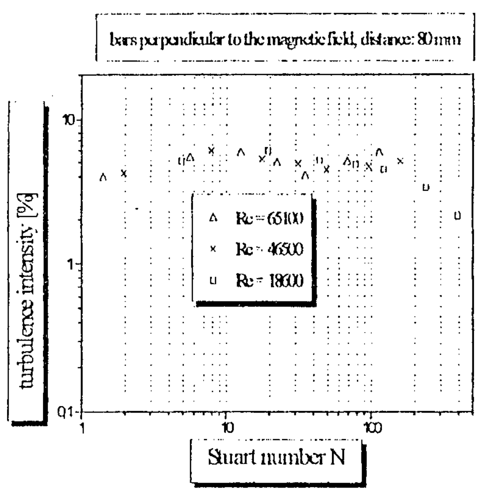
The longitudinal component of the flow velocity and their fluctuations were measured behind a grid of cylindrical bars in a turbulent sodium flow exposed to a transverse magnetic field. In the concrete case a wall thickness of 4 mm gives a wall conduction ratio of about 0.013.

The relative turbulence intensity ($\bar{u}'/\bar{u}$) will be presented as a function of the Stuart number N as well as the ratio Ha/Re for three different distances (80 - 305 mm) between the grid and the probe. Moreover, the rotatable installation of the inserted grid allows the choice of any angle with respect to the magnetic field direction.

Because of the high electrical conductivity of sodium measurements with Stuart numbers up to 400 (u_{SO}= 0.2m/s, B = 0.45T, Ha/Re = 150) are possible.

Distinct differences between the results obtained for both cylinder positions ($||$ and $\perp$ to $\vec{B}$) were found at all three distances behind the grid (see figures).





THE FLOW AROUND CYLINDER IN PRESENCE OF A MAGNETIC FIELD

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In a frame of a two-dimensional approximation of MHD equations [1] a solution of the task of the flow around cylinder is presented. Non-conducting cylinder in radius R and lengthways h is placed between two non-conducting plates. The latter are on the distance h opposite one another and are perpendicular to a uniform magnetic field **B**. An axis of the cylinder is in magnetic field direction. Due to flow generated hartmann currents, electro-magnetic braking force exists in the flow. Potential part of this friction force leads to a pressure redistribution in the channel and around the cylinder. A pressure gradient arises along the channel due to hartmann friction on the channel's walls.

Influence of a magnetic field on the flow is taking into account by adding à linear friction term in the Navier-Stokes equations:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = \nabla P + \frac{1}{\mathrm{Re}}\nabla^2 \mathbf{v} - \frac{\mathrm{M}}{\mathrm{Re}}\mathbf{v}$$

where $\mathrm{Re} = \frac{\rho V R}{\mu}$, $\mathrm{M} = \frac{2R^2 B\sqrt{\sigma/\mu}}{h}$

Taking into account the boundary conditions: $v_r\big|_{r\to\infty} = V\cos\varphi;\ v_\varphi\big|_{r\to\infty} = -V\sin\varphi;\ v_{r,\varphi}\big|_{r=R} = 0$

we have formulas for flow velocities in a stokes's approximation

$$v_r = \cos\varphi\left\{1 + \chi_-(r) - \frac{1}{r^2}\xi\right\};\qquad \chi_\pm(r) = \left[\left(K_2(\sqrt{M}r) \pm K_0(\sqrt{M}r)\right)/K_0(\sqrt{M})\right];$$

$$v_\varphi = -\sin\varphi\left\{1 - \chi_+(r) + \frac{1}{r^2}\xi\right\};\qquad \xi = K_2(\sqrt{M})/K_0(\sqrt{M});\ r = r/R;\ v = v/V$$

-- where $K_2()$, $K_0()$ àre Macdonald's functions. Notice, that the velocity distributions at $M>>1$, due to asymptotic behaviour of these functions, are slightly differ from those, which are for a potential flow around cylinder. They are differ from those only near cylinder's surface to satisfy to the boundary conditions. The thickness of the boundary layer is $\sim M^{-1/2}$. We can calculate the total resistance force of cylinder by solving an equation for pressure and knowing the value of viscous stresses on the surface:

$$F = 4\pi R^2 VB\sqrt{\sigma\mu}\cdot\xi\ ,\quad \text{where}\quad \xi \cong 1 \quad \text{at } M>>1.$$

The main part of this force is the resistance due to upstream and downstream pressure difference at cylinder. The ratio of viscous to pressure parts of this force is about $M^{-1/2}$. At $M>>1$ we can neglect by viscous friction on cylinder and to calculate the pressure distribution on cylinder and resistance force as for potential flow. Made it we have

$$\frac{(P - P_0)}{\rho V^2/2} = 1 - 4\sin^2\theta + \frac{4\mathrm{M}}{\mathrm{Re}}\cos\theta \qquad \text{where}\quad \theta = \pi - \varphi,\quad P_0 = P\begin{pmatrix}\varphi = \pi/2\\ r\to\infty\end{pmatrix}$$

The resistance force is the same, but $\xi = 1$. Taking into account a condition $\partial P/\partial\theta \geq 0$, we find a break-away point position θ_0 on the cylinder: $\cos\theta_0 \leq -\frac{\mathrm{M}}{2\,\mathrm{Re}}$.

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RESISTANCE OF CYLINDERS ORIENTED ALONG THE MAGNETIC FIELD IN LIQUID METAL FLOW

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There is a number of works concerning investigations of flow characteristics behind cylinders different orientation with respect to a magnetic field. However, the data relevant to cylinder resistance are not numerous. This work deals with study of the resistance of cylinders with different conductivity oriented parallel to the magnetic field. The experiment was carried out in a closed channel with rectangular section of 40x40 mm with eutectic alloy InGaSn. The turbulent flow in the channel was generated at the interaction of external vertical homogeneous magnetic field up to 1.5 T with the electric current up to 9 A/cm supplied by the DC source through two copper linear electrodes mounted flush on the lateral channel walls in the beginning of channel. The cylinders 5 mm in diameter were vertically dipped into the fluid through the hole in the upper cover placed at the distance of 450 mm from the channel entrance. Insulating and copper cylinders were used. The cylinders' tops were fixed on the stainless steel elastic plate. In both series of the experiments the lower end of the cylinder was placed 0.5 mm above the channel bottom. The cylinder resistance to liquid flow was proportional to the angle of its slope with respect to the vertical direction. This angle was measured by the Hall sensor which was placed on the top of the cylinder. The flow rate was measured by a potential probe. In the experiments the dependence of this rate on the supplied electric current was linear over the whole range of the magnetic field. The Reynolds number varied in the range of 400 to 3500 and the Hartmann number from 20 to 280. Both these numbers were calculated according to the cylinder diameter. According to our results the resistance of nonconducting cylinder can be significantly higher than that of the conducting one. For example, at the Hartmann number range of 20 to 100 and the small Reynolds numbers, Re=400, these resistances differ 2-fold. At moderate values of Reynolds number, the flow around cylinders of different types differ. The electrical current shorting out through the conducting cylinder redistributes electromagnetic forces near the cylinder and creates narrow zones of high and low pressure before and behind of the cylinder, so that resistance decreases, at least for Ha<100. At Ha=200, the resistance of conducting cylinder higher than that of the nonconducting one, these resistances differ 1.8 times. At large Reynolds number exceeding 2000 in the investigated range of the magnetic field, the pressure drop which is proportional to the squared velocity prevails over electromagnetic forces which are proportional to electric current, therefore the values of the resistances of both types of cylinders become equal.

MHD FILM FLOW MODEL FOR TOKAMAK REACTOR DIVERTOR PLATES

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The divertor design has always presented a challenge for physicists and engineers. The main concerns identified at the very early stages of tokamak reactor design studies were high thermal and particle loads resulting in thermal stresses, fast erosion and short life time of the divertor targets. In this connection attractive ideas of using liquid metal (LM) film to form a stress-free and erosion-insensitive working surface of the divertor target have appeared. Since the major concern remained with the problem of plasma impurity influx that might result from the plasma contact with LM, another divertor concept where the LM (Ga) film flow is to be used only for backside cooling of solid divertor plates has been proposed by the author with colleagues. The divertor plates in the form of inclined troughs fixed cantilevered are considered. The holder is combined with the manifold tube that has a set of orifices from which LM jets are ejected on the back cooled surfaces of the troughs. Hitting the plate's LM jets form a thin film that flows down like on inclined "ceiling" due to its own inertia as well as under the action of gravity force. A quasi-one-dimensional model has been developed for these divertor plates taking into account the following main assumptions:

- no external electric field is applied to the divertor plates;
- no plasma wind effects are to be considered (since the LM film flows on the back side of the divertor plate);
- no azimuthal (toroidal) movement is developed in the film;
- the contact resistance between LM and the plate is high enough, so the value of the plate own electric resistivity can be neglected;
- the divertor plate is short enough, so the magnetic field variation across its length can be neglected.

The final dimensionless equation for the film thickness as function of length is:

$$H' = \frac{Fr^{-1}\sin\alpha(1-\alpha'\cos\omega H/2)H^3 + \alpha'' H^2/2 + N(Y - ZH/2)H}{1 - Fr^{-1}\cos\alpha\cos\omega H^3 + NC_w B_h B_l H^2/2},$$

where

$$Y = \left(Ha^{-1} + C_w|B_h|H\right)|B_h| + Sign(B_w)\,2(HaW)^{-1}B_w H + C_h B_w{}^2 H^2;$$

$$Z = C_w\left(B_l B_h\right)' H + Sign(B_h)Ha^{-1}B_l'$$

α is the angle of plate axis inclination to horizon, ω is the plate roll angle (ω=0 for normal flow in a trough and $\omega=\pi$ for an upside down or "ceiling" flow);
all sizes are normalized by the initial film thickness, H_0, magnetic field components are normalized by the total magnetic field value, B_0, ' and " denote the first and second derivatives by dimensionless length,

$Fr = u_0^2 / gH_0$ is Froude number based on the initial film velocity, u_0, $N = \dfrac{\sigma B_0^2 H_0}{\rho u_0}$ is MHD interaction parameter, $Ha = H_0 B_0\sqrt{\sigma/\mu}$ is Hartmann's number,

$C_h = \dfrac{H_0}{\sigma\rho_i\delta_i}$ and $C_w = \dfrac{W/2}{\sigma\rho_i\delta_i}$ are the contact resistance factors

Calculating results have been obtained for typical conditions in the divertor developed within ITER (International Thermonuclear Experimental Reactor) project. Different boundary conditions (including magnetic field components), plate geometries and electroinsulating film resistivities were considered. The results confirm the feasibility of fast Ga films on the proposed ITER divertor plates.

DRAG FORCE AND TURBULENCE PRESERVATION IN THE CASE OF ALIGNED WITH MAGNETIC FIELD CYLINDRICAL PERTURBATOR

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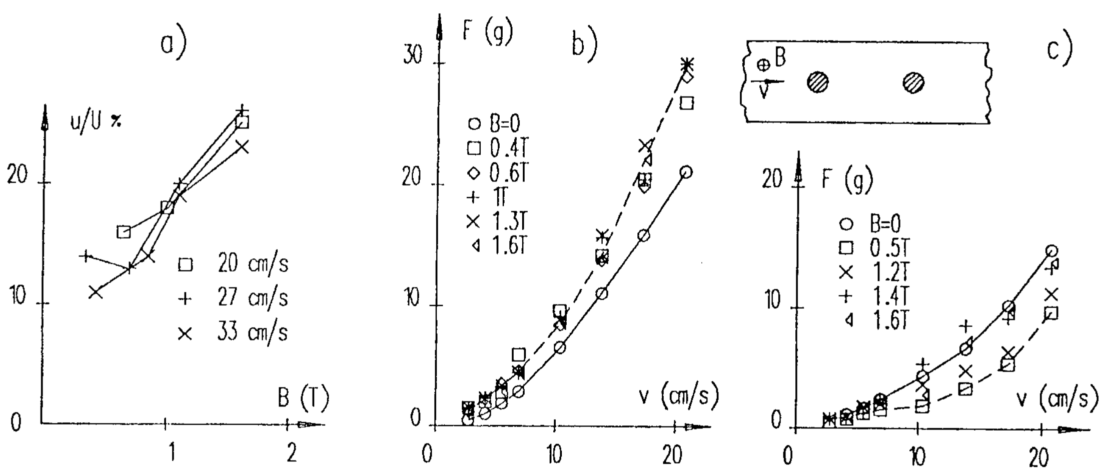
Turbulence promotion by mechanical perturbators can be considered as a well-known tool for heat transfer enhancement. But in ordinary hydrodynamics, as a rule, the energetical benefits is brought practically to zero by the introduced additional pressure losses. Ideas about 2D MHD turbulence allow to predict, that the situation can be changed when an accordingly orientated magnetic field is applied. As already shown in a number of experiments the MHD heat transfer can be enhanced to unusually high values since intense large scale 2D velocity perturbations can be preserved for long distances. In the same time one can not see direct reasons for essential growth of losses caused by the applied field which could raze the winning due to heat transfer enhancement. To confirm this last supposition the force acting on a perturbator was simply measured. By means of two vertical prongs an aligned with the field cylinder was fastened to a horizontal swing lying on two channel prismatic supports. The momentum caused by the acting on the body force was weighed by a counterbalancer returning the swing in equilibrium. The d = 10 *mm* isolated cylinder was immersed in a horizontal 350 *mm* long rectangular 40x40 mm^2 non conducting channel with *Hg* placed in a transverse field varying up to 1.8 *T*. To minimize the *M*-shapeness the channel was fed through a honeycomb of 39 plastic tubes. Fig."a" shows the expected introductionary result - growth of relative turbulence intensity with field in the centre of the channel 12d downstreamc body. Similar growth for approximate an order determined by the preserving action of the field was mentioned, for example, already in [1]. Fig."b" presents the main result - dependence of force on mean velocity at the same fields. The general conclusion is clear - the increase of force is much more less expressed. May be, it remains even in the bounds of accuracy, depending, first of all, on relation of the local acting velocity to the mean velocity. In the given case the upstream velocity was formed by mentioned honeycomb assuring a homogeneity of the profile with an 10% accuracy. The upstream intensity of turbulence was around 3%. The next result (Fig."c") reflects the way towards creation of perturbator system. At a distance 4d upstream the test object a similar cylinder was mounted. It means, the force was measured under conditions, where the cylinder plays the role of a repeater and is placed in the wake of the front perturbator. Expressed in dependence on mean velocity force behaves rather complicated. But again - no remarkable growth is being seen. Conclusion can be made , that effective perturbator systems can be designed too.



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MHD PERFORMANCE OF ELECTRICAL INSULATOR COATINGS ON ROUND PIPES AT FUSION REACTOR-RELEVANT CONDITIONS IN NaK AND LITHIUM

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Design calculations show that an electrically insulating layer is necessary to maintain an acceptably low MHD pressure drop for International Thermonuclear Experimental Reactor (ITER) liquid-metal-cooled components, which may include: (a) a Vanadium Alloy/Lithium breeding blanket, and/or (b) a NaK-cooled vacuum vessel, and/or (c) a NaK-cooled divertor. To begin experimental investigations of the MHD performance of candidate insulator materials and the technology for putting them in place, several new round pipe test sections were prepared. An aluminum oxide coating on 304 stainless steel was chosen as the first candidate insulating material/base metal combination because it may be used with NaK in the ITER vacuum vessel and/or the divertor; and MHD performance tests could begin quickly in Argonne's Liquid Metal EXperiment (ALEX) since NaK was already the working fluid in use at the time.

Following the NaK-Al_2O_3/SS MHD tests, the ALEX loop was converted to 300°C lithium service and testing was initiated on test sections fabricated of V4Cr4Ti alloys. Two test sections were fabricated and coated, one with a calcium oxide coating and one with an aluminum nitride coating.

Methods used to produce the electrically insulating layers as well as the microstructures of the coatings and sublayers are presented and discussed.

The length of the uniform magnetic field was approximately 1.8 m, and the maximum magnetic field strength was 2.0 T. The inside diameter of the test sections, the highest Hartmann number (M) and interaction parameter (N, using the pipe radius as the characteristic length) at which reliable MHD pressure drop measurements could be made were approximately as follows;

WORKING FLUID	**ID** (cm)	**M**	**N**
NaK	10.8	9200	10^4
Li	5.0	4200	10^4

A movable electrode device was mounted on the outside surface of the test sections and used as a diagnostic tool to assess the impact of any imperfections in the insulating layers. The overall MHD pressure drop and surface voltage distributions in both the circumferential and axial directions were collected for both NaK and lithium experiments. For the NaK test section, local MHD pressure gradient and local transverse MHD pressure differences were also measured. These results, gathered in the uniform field and fringing field regions, under a wide variety of conditions produced by varying the magnetic field, flow rate, operating temperature, and operating time at temperature, are presented and compared with ANL pre-test predictions.

FLOW STRUCTURE DOWNSTREAM OF A 90° BEND PERPENDICULAR TO THE MAGNETIC FIELD

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For the design of self-cooled liquid metal blankets for fusion reactors pressure drop and velocity distribution in the flow ducts must be known. A very common flow geometry are ducts with a 90° bend.
For fusion blankets using Pb-17Li as liquid metal relevant Hartmann Numbers Ha and interaction parameters N are Ha $\approx 10^4$ and N $\approx 2 \cdot 10^2$. Either electrically insulated duct walls or thin conducting walls are foreseen, with a wall conductance ratio C of $C = 0$ or $C \approx 0.05$.
For these MHD parameters the flow structure in the downstream leg of the bend is not known: in purely hydrodynamic flow ($Ha = N = 0$) inertia causes a large separation zone downstream of the inner corner; for inertialess MHD flow (Ha, N $\rightarrow \propto$) a flow distribution corresponding to potential flow is obtained. For the relevant MHD parameters it is of special interest to know if the inner corner acts as a promotor for two-dimensional (2d) instabilities which then could persist in a significant area of the downstream leg. This type of instability could be very favourable for heat removal from the duct walls without resulting in considerably increased pressure drop.
Mercury experiments in a 90° bend with rectangular ducts will be performed using a traversable multiple potential probe to measure two components of the flow velocity. MHD parameters are $80 < Ha < 650$, $0 \leq N < 500$ and $C = 0$, $C = 0.1$ and different radii of the inner corner $Ri = 0$; 10 and 20 mm. It is planned to measure the distribution of the mean velocity in the downstream leg, to determine the zone where instabilities occur and to analyse the instabilities by investigating spectra and coherence.
First measurements with insulated duct walls were performed. At $N = 50$ and $Ha = 620$ the velocity distribution is still very similar to that one for purely hydrodynamic flow whereas for $N = 230$, $M = 620$ the velocity profile becomes quite flat after a short flow path downstream of the bend. Strong fluctuations were detected which indicate an energy transfer from large scale perturbations to small scale ones.

EXPERIMENTAL AND NUMERICAL SIMULATION OF 3-D EFFECTS CAUSED BY IMPERFECTIONS IN THE ELECTROINSULATING LAYER ON TH MHD-FLOWS IN STRAIGHT CHANNEL

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The results of 2-D numerical calculations of fully developed flows in the channel with imperfections in the electroinsulating layer on channel walls showed that imperfections lead to a strong increase in pressure drop and strongly affect structure of the flow. But these cannot be directly applied for pressure drop increase evaluations in the conditions of fusion reactor blanket as the imperfections geometry (cracks of infinite length in flow direction) used in 2-D model does not correspond to actual situation of local cracks initiation and, respectively, calculated pressure drop increase is overestimated.

To study 3-D effects of local imperfections on the MHD flow in the channel with electroinsulating layer on the walls a set of experimental and numerical studies is started.

Experimental model is manufactured of organic glass as a rectangular channel : 2ax2b=20x100 mm. At first stage the imperfections are simulated by electroconducting inserts made of copper in the form of 100 mm long strips. 5 pairs of inserts parallel to magnetic field lines are placed on the longer walls of the channel (walls parallel to magnetic field). To simulate the electrical resistance of the circuits locking the imperfections in blanket conditions, the strips on parallel walls are connected by copper bar of variable electrical resistance. Electrical resistance can be varied in the range of $R_h = 10^{-6} - 10^{-3}$ Ohm, which is about the range typical for liquid metal blanket of fusion reactor.

Spatial resolution between the pairs of strips is 90 mm, preliminary estimations show that at such separation the effects of mutual interaction of imperfections can be studied. Simulation of the flow around a single pair of electrically connected strips (to eliminate the effects of interaction) is achieved by breaking off the locking electrical circuits ($R=\infty$) of other pairs.

Numerical simulation of 3-D effects of local imperfections on the MHD flow is made with the help of developed numerical code based on inertialess MHD-flow approximation. Developed code permits to calculate electrical potential in the whole domain (flow area, electroinsulating layer, walls, locking circuits) directly without making additional assumptions and introducing special boundary conditions on the interfaces. Benchmark calculations showed the workability of such approach.

EXPERIMENTAL AND NUMERICAL STUDY OF HEAT TRANSFER IN A SLOTTED CHANNEL

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Experimental and numerical results on heat transfer in a fully developed flow in a co-planar magnetic field in a slotted channel are presented.

Test section of rectangular cross section had following dimensions: 2ax2bxL=0.01x0.1x1.0 m. The channel was made of stainless steel, wall thickness was 1 mm, that corresponds to wall conduction ratio of 0.46 (In-Ga-Sn was used as a working medium).

Heat flux of 3600-7000 W/m^2 was applied to the longer (parallel to the magnetic field) wall of the channel on the length of 0.4 m starting from 0.1 m distance from the magnet edge that according to pressure and velocity measurements guarantees fully developed flow establishment in the whole heating area.

Temperature distributions were measured across the inner side of channel walls (under the heater) and in the flow along the direction perpendicular to the magnetic field. Experiments were carried out at constant velocity, Reynolds number was 250 (based on a) that corresponds to a laminar flow, no velocity fluctuations were observed in the flow under test conditions. MHD parameters were varied in the following ranges: Hartmann number Ha=0- 160, interaction parameter N=0- 100.

Numerical simulation of velocity and temperature profiles in the conditions corresponding to experimental ones was carried out by a finite difference code. Comparison of experimental and numerical results showed a good qualitative agreement, but numerical temperature profiles lie a little bit higher than experimental ones, that could be explained by some uncertainty in heat flux estimation.

Both, the results of numerical and experimental studies revealed Nusselt number decrease at low Hartmann numbers in the range of 0- 20. This effect results from side layers formation and drastic re-distribution of the flow rate across the channel cross section. Further increase of magnetic field is of nearly no effect on temperature distributions and on Nusselt number, respectively, thus, the M-shape velocity formation and development nearly does not affect heat transfer.

LIQUID METAL MHD FLOW TAILORING IN INSULATED RECTANGULAR CHANNEL: APPROACHES AND OPTIMIZATION

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The rectangular channel subjected to high heat load and strong magnetic field is considered in this study as a prototype element of fusion reactor first wall/blanket or divertor. The tailoring of liquid metal coolant laminar flow by MHD means is one of the methods for channel thermo-hydraulic performance enhancement.

The control of velocity distribution in the way so that more uniform temperature field in the channel cross section is provided can lead to a lower mean velocity, pressure drop or pumping power required to keep the maximum permissible temperature of walls below given restrictions.

The presence of high heat load on the first wall, considerable heat flux from the second wall (that is situated behind the first wall and liquid metal flow), volumetric nuclear heating of liquid metal coolant and walls as well as basic electrically insulated conditions for MHD flow are the specific features of this problem.

Several approaches for implementation of flow tailoring by MHD means are considered. These are the insulated partitions parallel to the flow and perpendicular to the magnetic field placed on the second wall; conducting strips made of stagnant liquid metal on the walls perpendicular to the magnetic field and others. These means can provide favorable velocity distribution that differs from the slug flow which is characteristic for insulated rectangular duct. The approximate formulas as well as direct 2-D numerical solutions are obtained for calculation of velocity distribution and pressure drop for the channels with flow tailoring.

On the base of solutions for velocity distribution the parametric 3-D calculations for temperature field are performed as well as optimization of channel thermo-hydraulic characteristics (pressure drop, pumping power, flow rate) for the case of ITER fusion reactor relevant data is fulfilled by proper choice of the geometry parameters. The increasing of Nusselt number for outlet cross section by factor of two and more is obtained. Considerable enhancement of thermo-hydraulic characteristics is demonstrated.

The possibility of gaining further improvement of MHD channel cooling performance by flow tailoring usage only on the part of the channel length as well as taking into consideration MHD instabilities which are highly probable for the high gradient velocity zones expected for considered types of flow are discussed in this study.

MULTI-CHANNEL EFFECTS IN MHD DUCT FLOWS OF ELECTRICALLY COUPLED AND PARTIALLY DECOUPLED SYSTEMS

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In many applications of magnetohydrodynamics, such as electromagnetic pumping, flow control or flow coupling, energy conversion or the design of self-cooled liquid metal fusion blankets, an electrical conducting medium flows in a system of ducts rather than in a single duct. In electrically separated systems the electrical currents are confined to the duct where they are induced. However, in electrically coupled systems currents induced in one duct are not confined to it and may enter neighbouring channels and modify the flow pattern. The effect of flow interaction, called multi-channel effect (MCE), affects the flow in the whole system and may reveal some peculiar features with respect to technical applications. Therefore, a lot of effort has been focussed on the investigation of MCE's.

An important multi-channel configuration in the fusion blanket technology is the system of U-bends, in which a liquid metal flow is perpendicular-parallel-perpendicular guided with respect to an external uniform magnetic field. In this special case global currents circulate between the two bends through all ducts, because of the opposite induced voltage in the ducts perpendicular to the magnetic field. The resulting MCE's cause unequal flow distributions in the individual sub-channels and lead to prohibitive pressure losses. To reduce MCE's in the fusion blanket application an electrical decoupling of the bends by means of insulating sheets or flow channel inserts (FCI) is foreseen.

In this article experimental results of the MHD-flow in completely electrically coupled and partially electrically decoupled multi-channel U-bends are presented and compared to numerical and analytical results. The partial electrical separation was achieved by means of electrically insulating foils placed between the side walls of the ducts perpendicular to the magnetic field. All other walls have the same electric conductivity as in the electrically coupled case. Experimental data for the pressure losses and the surface potentials on the duct walls show that the bend flows are highly inertial even at Interaction parameters N of more than 10^4. Both, in the electrically coupled and in the partially electrically decoupled multi-channel flow the inertial part of the pressure drop was found to scale with $N^{-1/3}$, as long as $N^{-1/3} \ll 1$. By extrapolating the experimental results obtained for high Hartmann numbers to inertialess flow conditions ($N \to \infty$) the numerically calculated values of the Core-Flow-Approximation are reached. The influence of the Hartmann number M on the global flow parameters is insignificant as long as $M \gg 10^2$. In the case of electrically coupled multi-channel U-bends a linear increase of the pressure loss with the number of coupled channels was measured, which is unacceptable to any fusion blanket design. The pressure measurements in the partially electrically decoupled U-bend flow exhibited that MCE's are still present, because electrical currents can short-circuit through the common Hartmann walls of the ducts perpendicular to the field. A linear increase of the pressure loss with the number of channels has been found like for the electrically coupled case. The slope of the linear increase of the pressure drop is smaller than in the coupled case. Compared to the electrically coupled configuration the electrical separation of the side walls in the ducts perpendicular to the field leads to a decrease of the pressure drop of about 30%. A complete suppression of MCE's is only obtained if all duct walls are electrically separated as previous measurements have shown.

Aluminium Reduction Cells and Interface Waves

WEAKLY NONLINEAR WAVES IN AN ALUMINIUM ELECTROLYSIS CELL

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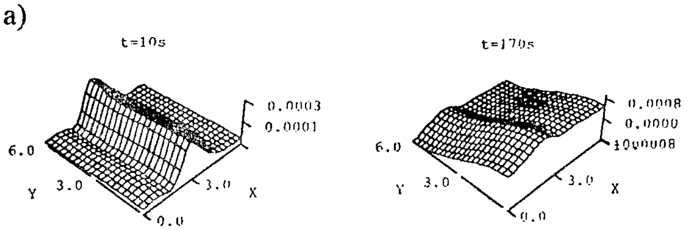
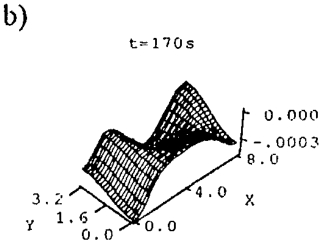
The interface between two fluid layers in aluminium electrolysis cells can be unstable for a "rotating wave" disturbance [T.Sele(1977), Metall.Trans.**8B**, 613]. A mathematical treatment of the problem by use of systematic perturbation expansions in a small depth parameter d and a small amplitude parameter ε even to the linear wave equation (coupled to the electric current equation) accuracy permitted to derive the stability criteria and to simulate the waves development [V.Bojarevics & M.Romerio (1994), Eur.J.Mech., B/Fluids, **13**, 33]. We extend the approximation accuracy to $O(\varepsilon\ )$, $O(d^2)$ and obtain a generalized Boussinesq equations for the interface, depth averaged velocities and electric current coupled problem. The potential and rotational parts of the velocities are equally important for the "rotating wave" development. The mathematical problem is reduced to a nonlinear wave equation and linear equations for the velocities and electric current, these are put in "weak" formulation and coupled equations in Fourier space are derived. The solution method is a discrete time stepping where the problem is linearized within a small time step and the resulting eigenvalue/eigenvector problem solved numerically by the high accuracy LAPACK routine DGEEV. The solution at a given time step is built as a truncated series by the computed complex time exponents with the corresponding to each of them series of eigenvectors, thus a series of Fourier components correspond to each single time exponent. The procedure is an extension of the linear stability problem.

a)



b)



Computed typical examples of the wave development are given in pictures a) and b). Initially a 0.001 m surface elevation of 1/20 cell length was used to start a solitary wave like perturbation. In the absence of the magnetic field this one dimensional wave runs the length of the cell, reflects and runs back without a change in the form. In the presence of the uniform B_z field a rotating wave starts to develop. A purely rotating wave can be achieved in a square cell: the example a) shows the solitary initial wave at 10s time and the superposition of the resulting rotating wave at 170s, i.e., after 4 periods of the "rotation" and the reflection (the periods were found to be equal to the computation accuracy). A different wave pattern was found for a typical elongated electrolysis cell where a stable wave at the same 160 kA total electric current and 0.001 T magnetic field produces a bouncing from the left to right traveling wave starting from the same initial perturbation, see the example b).

CALCULATION OF SLAG LINING FORM INFLUENCE ON METAL SURFACE DEFORMATION IN ALUMINIUM ELECTROLYSIS CELLS

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The main influence on metal surface deformation in electrolysis cells is due to action of electromagnetic force F_e, which is the result of interaction between vertical component of magnetic induction vector B_z and horizontal component of current density j_y. From hydrostatic approximation of Navier-Stokes equation, according to which $-\nabla P+F_e= 0$, if flows, that pressure drop P and, consequently, metal surface deformation H along longitudinal side x of cell can be expressed in following way: $\rho g\, \partial H/\partial x = j_y B_z$.

At given construction of current leads the distribution of B_z in the melt in the cell is fixed. But along with B_z the j_y, defined by the form of working space of electrolysis cell, namely, by the form and dimensions of side end bottom slag linings forming working space, also is responsible longitudinal metal surface deformation.

The order to investigate the influence of dimensions and form of slag lining on the magnitude of metal-electrolyte interface deformation and on hydrodynamic processes taking place in aluminium and in electrolyte, on the output in respect to the current the following calculation experiment for the case of transverse layout of cell at current strength 255 kA having baring current leads have been carried out. Four types of bottom slag lining have been investigated. 1.-without bottom lining, this case practically corresponds to the beginning of after-start-up period. Due to absence of bottom slag lining the component j_y in the metal is maximal, the maximal deformation is 30 mm. 2.- the width of slag lining is a half distance between side and anode. With formation of slag lining the working space of metal diminishes and, correspondingly, j_y diminishes, and as a result, the aluminium-electrolyte interface deformation diminishes up to 19mm. 3.-the width of slag lining equals to the distance between side and anode (δ=0.3m) it means, that the form of working space equals to the aspect view of anode on the bath bottom (according to accepted considerations it is optimal form of working space), as we expected the metal surface deformation becomes minimal and is, approximately ±2.8mm. Component of current density j_y is minimal. At favorable electrolysis process this space from corresponds to the heat equilibrium establishment at the and of after-start-up period. 4.-the width of slag lining is about two distances between side-anode. This is unfavorable heat regime, when slag lining can stretch nude aspect view anode component j_y in the aluminium changes the sign to opposite. According to formula the character of deformation also must change, which was observed in calculation experiment.

So, the diminishing of metal-electrolyte interface deformation in the bath of electrolysis cell at given construction of current leads realizes due to diminishing of j_y. The diminishing of j_y is achieved by optimization of working space form. By putting bars made from insulating material at the bottom of cell and placed in series along front and end sides of electrolysis cell we can created artificial slag lining on circumference of bottom, at this practically the optimal form of working space is being formed simultaneously, which leads to diminishing of after-start-up periods.

LOWERING OF STATIC METAL INTERFACE DEFORMATION IN ALUMINIUM ELECTROLYSIS CELLS USING MHD METHOD

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One of the important problems at developing construction of electrolysis cell is the diminishing of after-start-up period, which is characterized by low current efficiency and bad quality of produced aluminium. The after-start-up period óf the electrolysis cell is a time from start-up till setting up of a normal technological regime. During after-start-up period at the inner side of pit surface of the cell and around the bottom the slag lining is being formed, which is the layer of frozen electrolyte forming the working space of the electrolysis cell. The after-start-up period duration in the great extent depends on the time needed for the slag lining formation. For the diminishing of after-start-up period the bars from electroinsulating material can be installed on the bottom blocks of the cell, these bars must be located in series along the front and remote sides of electrolysis cell. This permits to form the artificial slag lining around the bottom, which practically leads to the optimal working space form, which results in diminishing of after-start-up period. The putting of bars allows to form discrete current-not-carrying zones, which gives the periodic changing of horizontal current density component in the melt. This, in turn, has an influence on the periodic change in the horizontal direction of metal interface deformation, which leads to the diminishing of resulting amplitude of 'longitudinal deformation and to the stabilization of electrolysis cell process, which follows from hydrostatic approach in Navier-Stokes equation, from which it follows:

$$\nabla P + \bar{F}_e = 0,$$

where ∇P - pressure drop, F_e - electromagnetic force.

Pressure drop, and correspondingly, metal surface deformation H along longitudinal side of electrolysis cell (x) can be expressed in the following way:

$$\rho g \frac{\partial H}{\partial x} = j_y B_z,$$

where j_y - transverse horizontal current density component, B_z - vertical component of magnetic field.

The magnitude B_z corresponds to the given construction of current busbars. The diminishing of B_z horizontal component leads to the diminishing of metal surface deformation H, but additional changing of j_y direction due to presence of discrete current-not-carrying zones leads to the changing of longitudinal inter surface deformation direction, which essentially diminishes longitudinal deformation component. If without bars there is sufficient parabolic deformation, then at the presence of bars, and with growing number of bars, the form of deformation amplitude changes, the height of peaks diminishes two times and more.

The installation of bars at the bottom of electrolysis cells can be done both in cells with longitudinal and transverse cells. The construction of bottom may be of any type: from blocks, stuffed or seamless. Anode blocks may be both self-baking or prebaked. At the same time the increasing of current density due to diminishing of metal surface working space leads to stabilization of electrolysis cell working process, and a possibility to work at optimal interpolar distance, also increases the output in respect to the current.

CALCULATION OF NONLINEAR 3D MAGNETIC FIELDS USING HYBRID INTEGRO-DIFFERENTIAL METHODS

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The important stage in studying magnetohydrodynamic processes in aluminium electrolytic cell is analysis and calculation of the magnetic field. Traditionally applied method of spatial integral equations for magnetization vector leads to enormously giant expenses of CPU time and computer memory for achieving necessary accuracy. The new method allows one to avoid these difficulties because it decreases three times the number of unknown variables and uses more effective numerical procedures.

The proposed method for numerical calculation of the three-dimensional non-linear magnetostatic fields can be applied to calculation of magnetic fields produced both by coils with the predefined spatial distributions of current density and by ferromagnetic objects with known non-linear magnetic properties. The method is based on joint discretization and solution of differential and spatial integro-differential equations for a scalar function — magnetic field potential — derived in magnetostatic theory. It is supposed that each region filled with a ferromagnetic substance is divided into unicoherent subregions (so that each object bisects the whole space into external and internal parts containing no holes). In this case the following equation is satisfied for the total scalar magnetic potential U

$$\operatorname{div}(\chi - 1)\operatorname{grad} U = 0$$

with the integro-differential boundary conditions

$$U(\vec{r}) = -\frac{1}{4\pi}\int_{\Omega_f} \frac{\chi \cdot \operatorname{grad} U(\vec{r}\,') \cdot (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3}\, d\Omega_f + U_c(\vec{r})$$

where Ω_f is the ferromagnetic volume, U_c is the magnetic potential produced by external sources (coils with currents), χ is the magnetic susceptibility, $\vec{r}$ and $\vec{r}\,'$ are the vectors corresponding to the boundary point and integration point respectively. The region Ω_f is divided into elementary tetrahedral finite elements. Inside each finite element the magnetostatic potential is approximated by a linear function based on reference values at the node points of tetrahedra. The resulting non-linear system of algebraic equations with respect to the potentials, specified for a discrete set of nodes, is solved numerically using a modified iteration method. As a result we obtain the potential, magnetization, field induction and field intensity inside ferromagnetic, which enable to calculate the magnetostatic scalar potential and magnetic field intensities correspondingly at any point of space. The program based on the proposed algorithm was used for simulation of magnetic field for typical constructive elements of aluminium electrolytic cell with real magnetic characteristics in presence the current coils. The results of calculations were compared with the output of the well known program GFUN [1].

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APPLICATION OF THE SPATIAL INTEGRAL EQUATION METHOD FOR ANALYZING THREE DIMENSIONAL MAGNETIC FIELDS OF POTS

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To develop, design and investigate operating pots (P) it is necessary to have complete and trustworthiness information concerning the distribution of magnetic field, created by the current of aluminium reduction, by busbar conductors and magnetized ferromagnetic elements (FE) of pot design. This problem is non-linear and essentially three - dimensional. The most acceptable method to solve it is the method of spatial integral equations (SIE). The complete field is represented as a sum of two components: field $\vec{H}_c$, created by all current conductor (CE) elements and calculated by Bio-Savart law; and field $\vec{H}_m$, produced by magnetized FE. So, for complete field in FE taking into consideration the real non-linear magnetization curve $\mu_r(|\vec{H}|)$, we have an integral equation :

$$\frac{1}{\mu_r - 1}\vec{M} = \vec{H}_c + \frac{1}{4\pi}\iiint_{V_m}\left[3\frac{\vec{M}\circ\vec{r}}{|\vec{r}|^5}\vec{r} - \frac{\vec{M}}{|\vec{r}|^3}\right]dV_m$$

where $\vec{M}$ is vector of FE magnetisation. Here the integration follows V_m of FE area.

Using the automatic FE discretization, this equation is reducing to the system of non-linear algebraic equations. The system matrix (thanks of symmetrization and normalization of elements) is symmetric and positively defined. That's why to solve it we can use the method of conjugate gradients with non-complete solution on linear iteration. To impove the convergence of solution on non-linear interations it is introduced a moderating factor.

The desired magnetic field at operating area is defined by superposition of FE magntetic fields, calculated by known values of FE and CE magnetization.

Based on SIE method, the system programs for calculating three-dimensional magnetic fields at operating area AE *"MAGN"*, was tested and is succesfully operating at Aluminium Magnesium Institute, St. Petersburg during some years. The system identification, realized by series of natural measurments and positive experience of its using confirm both the rightness of calculation method choice and correctness of its realization. For its further development- increasing the accuracy and expending the system possibilities, some improvements are now under investigation and realization.

CALCULATION OF THREE DIMENSIONAL CURRENT DENSITY DISTRIBUTION IN ALUMINIUM ELECTROLYZER

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For analysis of hydrodynamic processes in aluminium electrolyzer the detailed information about current density distribution in metal and electrolyte layers is quite essential. The following peculiarities of the problem are to be taken into consideration when calculating this distribution.

1. The shape of the surface between electrolyte and metal layers may influence significantly on resulting currents.

2. The configuration of current region and type of boundary conditions depends on the shape of crust.

3. The motion of melted aluminium in presence of external magnetic field leads to appearance of additional electric-field strength and must be taken into consideration when calculating currents in this region.

At the same time evidently the shape of the crust and of the metal - electrolyte interface depends on thermo- and hydrodynamic processes and therefore on the calculating current's distribution.

In order to solve this complex problem the 3-D finite element method (FEM) for scalar potential U was applied. The current region (anode, cathode, metal and electrolyte layers) was discretized into tetrahedral elements and second order shape functions were introduced in each tetrahedron to approximate the unknown potential. The whole problem was subdivided into three quasi - independent parts :

1. Calculation of current density in anodes and electrolyte layer. When formulating this part of the problem we assumed potential to be constant at the surfaces of anode rods and at the lower surface of electrolyte layer. The shape of the latter one can be varied if necessary.

2. Calculation of current density in cathode. The potential at the upper surface of the region assumed to be constant except its part, screened by crust, where normal component of current density was forced to be zero.

3. Calculation of current density in metal layer. As boundary conditions for this problem distribution of normal component of current density, calculated at two steps, described above was used. Evidently this problem is incorrect because Neuman conditions are assumed in every point of region's boundary surface. That is why the special regularizing procedure was used. Instead of initial Poisson equation for electrical potential in moving media the following differential equation was taken into consideration:

$$div\,(\gamma\, grad\, U) + \lambda U = div\,(\gamma\, \boldsymbol{V} \times \boldsymbol{B})$$

where γ is conductivity of melted aluminium, $\boldsymbol{V}$ is velocity of moving media $\boldsymbol{B}$ is induction of magnetic field and λ is regularizing factor. This equation with Neuman boundary conditions has the unique solution and may be solved using FEM. When $\lambda \rightarrow 0$ this solution coincides with solution of corresponding Poisson equation if additional gauging condition $\int U\, d\Omega = 0$ is accepted.

The calculated distribution of current density is to be used for further magnetic field calculation and analysis of hydrodynamic processes using FEM technique at the same global tetrahedral mesh.

OSCILLATION FREQUENCIES IN REAL ALUMINIUM REDUCTION CELLS: ANALYSIS AND NUMERICAL COMPUTATIONS

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Interface motions between aluminium and electrolytic bath are well described in the frame of the classical MHD theory for incompressible fluids.

In this theory, and within a very good approximation, these motions can be represented by sums of two displacements: a steady one, corresponding to a time independent solution of the MHD equations and a small time dependent one satisfying a linearized version of the same equations.

An algorithm allowing to compute eigenmodes and eigenfrequencies, and thus to obtain the general solutions of the linearized equations, is presented. The computation is performed in several steps. In the first one the gravitational modes are derived with the help of a block inverse power method. In the second one a Ritz-Galerkin approximation is used on the function space given by the span of the gravitational modes.The calculation is then achieved through an iterative procedure which leans both on a fixed point method and on the Ritz-Galerkin approximation, mentioned above, but applied to the span of the functions obtained in the preceeding step of the iterative procedure; it moreover makes use of an analytic continuation procedure during which the total electrical current reaches its rated value.This rather sophisticated algorithm allows us to circumvent difficulties resulting from possible degeneracies of the spectrum which can appear for some values of the total current, that is during the analytic continuation, mentioned above. Numerical results performed for industrial cells are exhibited. They take the following conditions and effects into account:

- the real geometry of the cell including ridges and edges,
- currents distributions obtained through measurements performed on the cell,
- the full bus bars arrangements surrounding the cell,
- induced currents entering computations of both velocity and induction fields,
- ferromagnetic effects due to the steel envelop in which the cell is located.

The complex frequencies corresponding to the different oscillation modes computed are described in the complex plane as function of the total electrical current crossing the cell.

Calculations are performed for cells corresponding to both side-to-side and end-to-end arrangements. The obtained results are compared to the frequencies derived, for the same cells, from a Fourier analysis performed on recordings of the anodic currents measurements.

Effects on the motion stability due to the distribution of the current density within the cell and to magnetic induction and velocity fields are studied on the basis of the performed numerical investigations. In particular it is shown that, for increasing values of the total electrical current, effects due to electromagnetic forces consist in displacements of the frequencies along the real axis; if during these diplacements two frequencies are becoming equal, the system may exhibit unstabilities for larger values of the total current. In some cases distabilysing effects, due to the velocity field, may be present; they are especially affecting the lowest frequencies.

Stability criteria, based on a mathematical analysis of the equations are also discussed, on the basis of a Ritz-Galerkin approximation applied to two close eigenfrequencies.

WAVE PROPAGATION IN A THREE-LAYER ELECTRICALLY CONDUCTING FLUID

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A new problem of nonlinear water wave propagation for a three-layer electrically conducting fluid in the presence of magnetic field $(H_{01}, 0, 0)$ is stated and analysed. Cartesian coordinate system x_1, x_2, x_3 is taken with the origin at the middle undisturbed surface $x_3 = 0$ of the intermediate layer. A weak electroconductivity approximation (noninduction approximation) of MHD-model is used so that characteristic parameter $N = R_m P_H$ is involved, where $R_m = c_3 2h\mu\sigma$, $P_H = \mu H_0^2/(\rho_1 c_1^2)$. The vertical three-layered structure of plane problem is given as the upper (index 1) and lower (index 2) half spaces, $z > h$ and $z < -h$, with uniform densities ρ_1 and ρ_2, respectively, and the intermediate layer (index 3), $z \in [-h, h]$ with a uniform density ρ_3, under the condition $\rho_1 < \rho_3 < \rho_2$. On the interfaces the kinetic and dynamic conditions are satisfied from which follow that the fluids do not penetrate each other. The fluid is assumed to be inviscid and incompressible, the motion irrotational that is possible in the case of plane problem (Shercliff, 1965). It allows to introduce the velocity potentials according to $v_k = \varphi_{,k} (k = 1, 2.3)$ and present the nonlinear statement in terms of potentials φ_1, φ_2 and φ_3. After scaling the two basic parameters appear: the parameter of nonlinearity $\alpha = a_{max}/2h$ and the parameter of dispersion $\beta = (2h/L)^2$, where a_{max} is the maximal amplitude and L is the characteristic length.

To derive the evolution equation the asymptotic-heuristic approach is used (Selezov & Korsunsky, 1991), which includes the following steps: (i) dispersion equation for a linearized problem $D(\omega, k) = 0$; (ii) longwave approximation of this equation; (iii) one-to-one correspondence allows to use $\omega \to -i\partial/\partial t$, $k \to i\partial/\partial x$ and reestablish a linear part of the evolution equation; (iv) perturbation method applied to the system without dissipative and dispersion terms leads to nonlinear Schrödinger equation.

It is shown that in leading order the analysis of the three-layer system for asymmetric wave mode is reduced to two-layer one. That is the leading longwave asymptotic approximation of the order $O(k)$ (k is the wave number, $k \ll 1$) corresponds to a two-layer fluid catching only the geometrical presence of intermediate layer. As a result the velocity of wave propagation depends only on the intermediate thickness $2h$ but does not depend on its density ρ_3. And besides the velocity of wave propagation decreases with increasing $2h$.

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INTERFACIAL INSTABILITIES IN ALUMINIUM REDUCTION CELLS

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The cryolite-aluminium interface in an aluminium reduction cell may be destabilised by two distinct MHD effects. (1) A perturbation of the interface causes a redistribution of the electric current flow through the cell, and the ensuing magnetic force perturbation may reinforce the disturbance. (2) MHD forces establish (largely horizontal) circulations in both the aluminium and cryolite layers, leading to a Kelvin-Helmholtz instability at the interface.

Our aim is to analyse both instabilities assuming that the circulations $\mathbf{U}^1$ and $\mathbf{U}^2$ in the aluminium and cryolite layers are given. In practice the $\mathbf{U}^i$ may be calculated using numerical packages, or a simple analytic model may be used.

The perturbation η of the interface is expanded in the form,

$$\eta = \sum_{n=0}^{\infty} a_n(t) E_n(x, y)$$

where the $E_n(x, y)$ are the eigenfunctions of the problem,

$$\nabla^2 E_n + \lambda_n^2 E_n = 0, \qquad \nabla E_n \cdot \hat{\mathbf{n}} = 0 \quad \text{on } \partial C,$$

∂C denoting the lateral cell boundary. Since both the cryolite and aluminium depths are small compared with the horizontal cell dimension, we assume the perturbation flow can be written in the form,

$$\mathbf{v} = \nabla\phi(x, y, z) + \nabla\psi(x, y) \times \hat{\mathbf{z}}$$

where the first term represents an irrotational flow corresponding to the interface perturbation, and the second a rotational circulation independent of the vertical co-ordinate z. We expand ϕ and ψ in the forms,

$$\phi = \sum_{n}^{\infty} b_n(t) f_n(z) E_n, \qquad \psi = \sum_{n}^{\infty} c_n(t) F_n,$$

where the F_n are similar to the E_n, but vanishing on ∂C. By taking inner product of the perturbed equation of motion with suitable test functions we obtain evolution equations for the coefficients which can be written in the form,

$$A\dot{\mathbf{x}} = -B\mathbf{x},$$

where A and B are constant matrices determined from the magnetic field and the circulations. The array $\mathbf{x}$ contains the coefficients a_m, b_m and c_m.

Results show that mechanism (1) is particularly destabilising when two natural wave frequencies of the cell are almost equal. Instability growth occurs via a resonant MHD coupling between the two modes. Mechanism (2) is also destabilising, and both effects depend crucially on the layer depths, and the magnetic field due to currents in the bus bars.

AN EXAMPLE OF INTERFACIAL WAVES GENERATED BY A ROTATIONAL FORCE FIELD

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We began to investigate analytically the perturbations in the aluminium/cryolite interface of an Hall-Heroult cell caused by the presence of a moving carbon dioxide gas bubble distribution on the anode undersurface. Perturbation of the electric current about such bubbles generates a moving rotational force distribution which results in small lengthscale waves in the aluminium/cryolite interface. A number of simple analytic models were solved by Fourier series expansion and the results from these models suggest that waves generated by this mechanism in an actual cell are negligible. However, several of the models displayed a system of forced waves propagating away from the model boundaries, which seems unusual considering the global nature of the applied force distibution.

We thus turn our attention to these waves in a more theoretical emphasis, and present a description of the waves' behaviour. We consider a further model which can be solved asymtotically via Fourier transform and the method of stationary phase. This solution enables us to explain some of the waves' behaviour, and to find an expression for the velocity of the wavefront as it moves away from the boundary.

MHD Power Generation

THE LOCALLY LIQUID-METAL MHD GEO-POWER STATION DEVELOPMENT DESIGN

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The liquid-metal MAD (LMMHD) power station thermo-, hydro- and electrodynamic investigations results are performed in this report. This LMMHD power station is intended for low-temperature (150...130) °C heat sources utilization. The locally LMMHD Geo-Power Station unified module design is developed. The conduction direct current LMMHD-generator (LMMHDG) is building on the Faraday's principle with sectionalizations electrodes is worked out. The riser channel is build up as air-lift system is applyed water drops introduced by original mixer. To supply heat for the facility the liquid metal housing-tubes (shell) liquid-vapor heater is designed on the thermosyphones principle.

At the optimization stage such parameters as height of the gravity loop(ho), electrodes lenth(L), depth to width MHD channel ratio (h/w)are modified at the diapasone: ho = 3...30m; h/w,= 1...50 L = 0,1...1,5. Load coefficient is issued 0,01...0,97.

The liquid-metal MHD (LMMHD) power station main performances are as follows

Working fluid		In-Ga-Sn
Working fluid temperature (saturated vapor), °C		150
Thermal power input, kW		210
Liquid metal volume flow rate, m^3/s		0,016
Liquid metal downflow(up) channel height, m		10
LMMHDG channel dimensions, m		
- depth		0,251
- width		0,013
LMMHDG electrodes length, m		0,5
MHD voltage, V		4
MHD load current, kA		4,1
Magnetic field, T	up to	1,0
Unit power, kW		5
MHD generator efficiency		0,53

To increase power the LMMHD power station LMMHD facilities are connected in one plant according to the power requirements. Problems of the geothermal, industrial waste gases (~ 600 °C) utilization by locally LMMHD power stations are exemined. Facility unified module construction is permit to create power station of the requirement performance.

The LMMHD power station performances increasing by means of the optimization up-channel operation to create monodyspersion two-phase flow with requirement drops dimensions and void fraction are discussed.

The facility detail design is worked up.

EXPERIMENTAL AND THEORETICAL RESEARCH OF THE HIGH TEMPERATURE ELECTROMAGNETIC PUMPS

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In the report results of the investigations of the induction electromagnetic pumps (EMPs) and their models developed at the Institute of Physics, Special Design Office and Research Works "ENERGIA" are presented.

Low power high temperature EMPs (output in one hydraulic line, up to 100 W) have been designed for the cooling systems of space nuclear reactors.

Special operating conditions make demands on reliability of EMPs design, minimization their mass and overall dimensions characteristics and high energetic values. On this account in the report review have been carried out as follows:

- optimization of an integral function in the form of reduced mass, specially introduced to high temperature EMPs;
- determination of the free parameters of the end effect model for optimization of inductor structure and non-magnetic gap basing on experimental tests on liquid metal loops in the wide range of defining parameters (R, Ha, t, Q);
- development of special experimental facilities for EMPs tests including multi-channel aggregates in the conditions very close to real one's;
- investigation of the EMPs at the temperature range close to maximal;
- selection of appropriate construction and isolation materials for EMPs and estimation of effective heat exchange among pump constructive elements.

Performed heater, hydrodynamic, energetic and other calculations and experimental tests demonstrated possibility to develop high temperature EMPs for the cooling systems of nuclear power reactors.

Gained conclusions and recommendations models of real EMP designs created for stand tests are illustrated.

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TIME DOMAIN ANALYSIS OF MHD GENERATOR PERFORMANCE BY A 3D MODEL

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This paper shown an important improvement of the author's 3D circuital model [1-4] suitable to investigate the macroscopic behaviour of the MHD Linear Generators in stationary conditions. This improvement consists in removing the assumption of no-time dependence of the lumped parameters which generate the equivalent network of the model: in the present work these parameters are taken into account as time functions. This permits to evaluate the effects of non uniform gas discharge in MHD energy conversion. In fact this phenomenon is always present in MHD generators and it is the main cause of the electrical power fluctuations on the external loads. To analyse this aspects of MHD conversion, the present 3D model is a good instrument as described in the paper. For lumped parameters determination, the main physical gas characteristics have evaluated either by experimental measurement[5-6] or by theoretical assumptions [7]. The external magnetic field, the gas velocity, the input thermal power and so on, have also been deduced from experimental tests. The gas conductivity time dependence has been taken into account by means equivalent ideal voltage generators which have been defined by appropriate time functions: when the gas stream is assumed active this generator simulate an increase of conductivity, while it makes the opposite action when the stream is absent. In addition, to simulate in a better way the real case, a suitable algorithm using in the resolution of the network has been adopted: all time dependent voltage generator have not been assumed simultaneously making an increment action on the gas conductivity: some of them will be positive, others negative, others will be by-passed. The solutions have been obtained by the application of an iterative method in the time domain with various calculation step amplitude to test the model sensibility. The results of the simulations have been compared with experimental tests [6] to verify the suitability of the model and its degree of agreement with the real cases either in stationary conditions [1-4] or in the time domain analysis.

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INTEGRATED EXPERIMENTAL SYSTEM FOR TESTING THE ETGAR CONCEPT USING DIRECT CONTACT BOILING IN LIQUID LEAD

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The steam in the LMMHD ETGAR (gravitational) system will initially be generated by a conventional boiler and then injected through the mixer to the hot lead.

In order to further reduce capital and operation costs of the ETGAR systems, it is proposed to inject the thermodynamic fluid in its liquid phase (instead of steam) into the hot liquid metal in the "riser" branch of the loop. The boiling of the volatile liquid in this case occurs under direct contact with the liquid metal, and thus will avoid the need for an expensive external steam generator. It is also anticipated that the boiling process will lead to mixing of the two-phase flow and hence a decrease of the slip between vapor bubbles and liquid metal (higher loop efficiency).

The applicability of this new idea will be tested in an integrated experimental system - the "OFRA"system - which is under final stages of construction.

The OFRA facility described in this paper will simulate a real LMMHD ETGAR loop and is designed to operate with lead and eutectic lead/bismuth, at temperatures up to 480^0C, with the following research targets:

(1) Studies on the direct contact boiling phenomena of a multi-droplet bed of water in lead;

(2) Influence of different additives (surfactants, foaming materials etc.), dissolved in the lead, on the two-phase flow characteristics, namely, void fraction distribution and phase velocity ratio, flow configuration and overall system performances;

(3) Studies of water reaction with molten lead over a wide range of temperatures, pressures and flow rates;

(4) Testing of the lead reaction with the construction materials in the presence of liquid/vapor water.

TWO-PHASE FLOW STUDIES OF MERCURY-NITROGEN IN A SIMULATED LIQUID METAL MAGNETOHYDRODYNAMIC ENERGY CONVERTERS OF GRAVITY TYPE

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Liquid Metal MagnetoHydroDynamic Energy Converters(LMMHD EC) of gravity type have been recently proposed for variety of heat sources for electrical power generation[1]. In these systems, vertical two- phase flows consisting of steam and high density liquid metals like lead or lead alloys take place in the riser pipe. The design of optimum LMMHD EC and for scaling up of the system requires accurate modeling of two-phase flows. The most important parameter which governs the two-phase flow is the void fraction. Most of the empirical relations for void fraction are based on either air-water/steam-water or by indirect measurements. The accuracy and the range of applicability of these relations have to be verified for liquid metal two-phase flows.

Experiments have been conducted in a nitrogen-mercury simulation LMMHD EC facility. Time averaged void fraction was measured for various flow rates using gamma-ray attenuation method with ^{60}Co of 75 mCi radioactive source[2]. Corrections for cross-sectional variations and dynamic fluctuations in the void fraction as well as error because of finite beam size of the gamma ray have been applied to improve the accuracy of measurement. Measured void fraction and pressure profiles were compared with predicted values based on well known empirical relations for void fraction. In addition, the data was compared with values based on bubble/slug flow models, which take in to consideration momentum equation of the gas explicitly. The results of the analysis will be presented in the paper.

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INTERACTION OF A PLASMA STREAM WITH DISPERSE PARTICLES UNDER THE INFLUENCE OF TRANSVERSE MAGNETIC FIELD

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As the magnetic field affects the heat and mass transfer processes at plasma-particles interface boundaries, it is important, in connection with MHD converters as well as new material techniques, utilizing plasma discharges, to study interaction of plasma stream with disperse particles in a transverse magnetic field. In the present paper we are interested in a study of disperse metal particles (Ti, Al) unsteady heating, evaporation and oxidation processes in a low-temperature free flow plasma stream injected into a transverse magnetic field. These investigations are important because the fundamental processes involved in such a system can be generally applied to other plasma stream-disperse particles interactions. The experimental investigations were performed by using the disperse free flow argon-air plasma injected into transverse magnetic field with field strength varying up to 1.0 T. To study the external magnetic field effect on the plasma and particles interaction, the evolution of free plasma flow and disperse particles temperature, composition and radiation distribution across and along the disperse plasma flow was measured. These measurements were carried out by means of absorption and emission spectroscopy, using the spectrometers DFS-8 and DMR, coupled with the recording systems. The disperse particles size distribution function and phase structure studies were performed using transmission electron microscopy and *X*-ray diffraction methods.

An interesting feature observed in this paper is the field induced free flow radial expansion resulting in the formation of uniform temperature distribution over the initial plasma flow cross-section. This process is accompanied by the decrease of plasma and disperse particles temperature ($\Delta T \sim 200 - 300^0$) in the central part of plasma stream ($R = 0$). From analytic viewpoint, the disperse particles unsteady heating and evaporation in the plasma flow are the temperature determined processes [1] and, therefore, under the influence of transverse magnetic field, the evolution of these processes in plasma flow in general is determined by the strength of an external magnetic field. The analysis of experimentally observed field-induced disperse particles temperature, radiation, average size and chemical composition changes as the function of magnetic field strength in this paper are presented.

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Dynamo

DYNAMICALLY CONSISTENT LAMINAR DYNAMOS

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The paper presents some results on kinematic spherical laminar dynamos and their dynamically consistent counterparts. We consider a spherical body of an incompressible electrically conducting fluid in non-conducting surroundings.

In the kinematical case a velocity field is assumed which is symmetric about an axis and the corresponding equatorial plane and satisfies the no-slip condition at the boundary. The critical magnetic Reynolds number and the corresponding magnetic field pattern are calculated.

In view of a dynamically consistent model the body force is determined which is able to generate and to maintain the above velocity field. Starting with this body force and certain initial conditions the evolution of the velocity and the magnetic field is followed up. Results for various magnitudes of the body force, several initial conditions and several assumptions concerning parameters as the Prandtl number have been obtained and will be discussed.

In the basic equations fluid velocity and magnetic field are expanded in series of certain decay modes. For our numerical approach these series are truncated and the remaining finite set is integrated. This method is described in some details elsewhere [1 2 3] .

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DYNAMICALLY CONSISTENT SPHERICAL MEAN-FIELD DYNAMO MODELS

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Spherical mean-field dynamo models are considered which involve in part the interaction between the magnetic field and the motion of the electrically conducting fluid. Whereas the influence of the magnetic field on the small-scale motions responsible for the α-effect is ignored, the effect of the Lorentz force due to the mean magnetic field on the mean motion is taken into account. The magnetic field and the velocity are expanded in series of certain decay modes. The basic equations are so reduced to an infinite set of ordinary first-order differential equations for the coefficients depending on time.[1 2 3]
The evolution of the mean magnetic field and the mean motion is studied numerically for two different boundary conditions for the motion, viz., the no-slip condition and the condition of a stress-free surface. Several steady states have been found with different symmetries about the rotation axis and the equatorial plane of the fluid body for several Taylor numbers and magnetic Prandtl numbers. The stability of these states clearly differs for the two boundary conditions. In one case an evolution to an axisymmetric state is preferred in the other case to a non-axisymmetric one. In addition to the steady solutions with simple symmetries also an oscillatory mixed-parity solution has been found.

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GENERATION PROPERTIES OF A LABORATORY MHD DYNAMO MODEL

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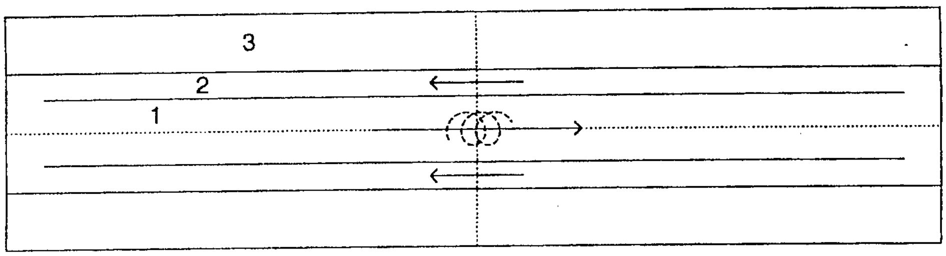
In order to prepare a new experiment with an updated version of our laboratory MHD dynamo model [1] we have optimized the generation parameter $Rm = \mu_0 \sigma V_{max} R_1$. The mathematical model used consists of three coaxial cylindrical conductors with length L and radii $R_1 < R_2 < R_3$:



1) Central swirling stream with uniform axial velocity v_z and rotation rate ω.
2) Counterflow uniformly reversing the whole central flow-rate without rotation.
3) Stagnant conductor with no movement.

The generated magnetic field in each of the conductors and in an outside insulator is presented by Bessel functions [2]. The electrical resistances r_{12}, r_{23} of walls separating fluid conductors 1, 2 and 2, 3 are included in boundary conditions and measured in units "thickness of the equiresistant fluid". The agreement of all boundary conditions with zero field at infinity leads to the critical value of Rm.

Due to technical reasons the following values are used $r_{12} = r_{23} = 0.08R_1$ and $R_1 : R_3 : L = 1 : 3.6 : 25$.

Optimization of other parameters leads to $Rm^* = 18.99$ when $R_1 : R_2 = 1 : 1.77$ and $\omega R_1 = v_z$.

The table below contains deviation $\delta Rm = Rm - Rm^*$ of Rm if some parameter is modified with respect to the above configuration. The columnn δW contains percent of saved (-) or excess (+) hydraulic power in result of the modification:

$\delta W/100 = (Rm/Rm^*)^3 - 1$.

Diagrams, illustrating other aspects of generation will be presented at the conference.

δRm	$\delta W\%$	Modification
-1.18	-17	$r_{12} = 0$
-0.30	-4.7	$r_{23} = 0$
+0.37	+6.0	$R_1 : R_2 : R_3 : L = 1 : 1.65 : 3 : 25$
-2.42		$L = \infty$

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PROJECT FOR A LIQUID SODIUM MHD DYNAMO EXPERIMENT

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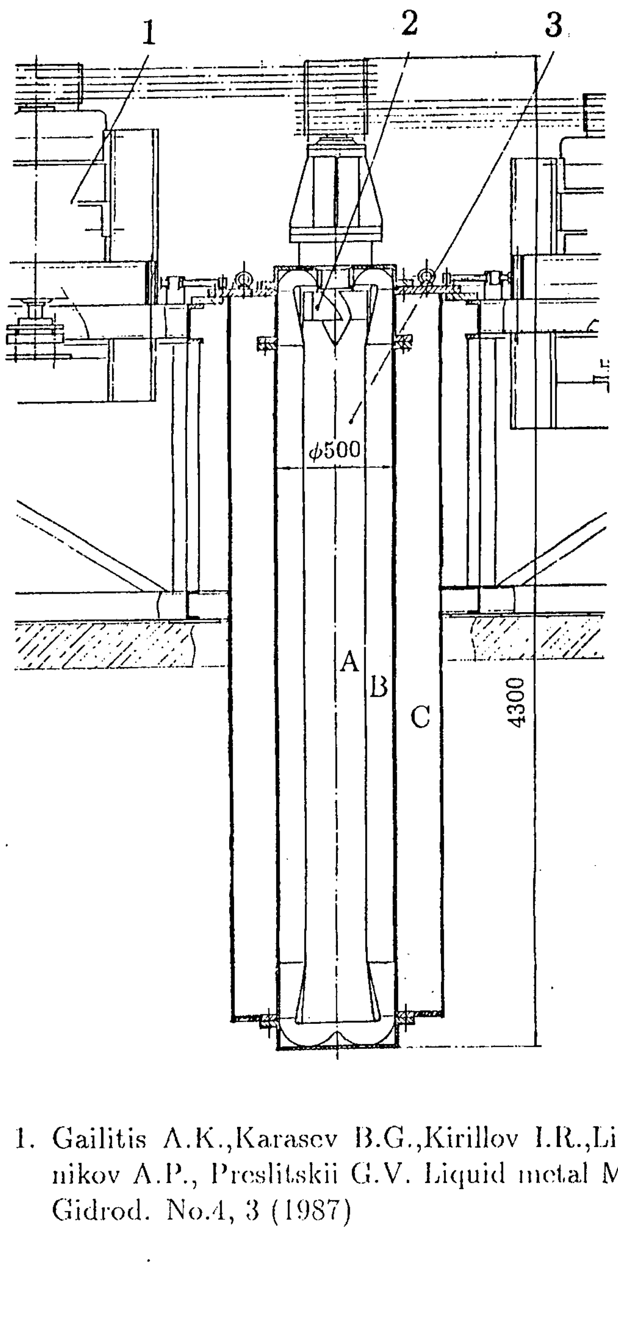
We are preparing an updated experiment [1] in which a liquid sodium flow should generate a magnetic field likewise as a convection of molten Earth core generates the Geomagnetic field. Reproduction of a natural phenomenon inside a laboratory is not an easy task and the scale of the experiment is larger as usual.



The experimental device is under construction. Two 55 kW motors 1 are rotating a turbine 2 which forces the liquid sodium to circulate inside an annular vessel 3, part of which is located in the basement of sodium lab. The sodium flow is directed by two thin electroconducting coaxial partition walls. In the central channel *A* sodium is flowing down from the turbine. In the coaxial counterflow channel *B* the flow is directed up to the turbine. In outer part *C* of the vessel the sodium is moveless, it serves for electrical connection.

The turbine is designed also to swirl the central flow. About 80% of the initial swirl is maintained by inertia at the downstream end of the central channel. The swirling is stopped after the flow is reversed. According to the computation results [Gailitis & Gerbeth, this volume] the generation of an alternating magnetic field should start at the flowrate 0.6 m^3/sec.

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NUMERICAL STUDY OF CYLINDRICAL DYNAMOS WITH AXISYMMETRIC FLOWS

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As has been emphasized by the Riga MHD laboratory, fundamental knowledge in MHD turbulence would result from an experimental device producing an observable dynamo effect. The main obstacle to such a realisation lies in the critical velocity and length scales which must be achieved in a liquid metal flow. The cylindrical geometry seems more relevant to an experimental facility than spherical or homogeneous periodic flows where most results on the fluid dynamo effect have been obtained up to now.

Numerical simulations are particularly helpful to select an efficient and realistic flow configuration. The dynamical equations are numerically integrated in time using a pseudospectral scheme for the azimuthal and axial derivatives and a compact finite-difference scheme for the radial derivatives. The external medium is assumed to be non-conducting.

The selection of a flow topology may be performed in the kinematical dynamo framework and results concerning this first step will be presented. To examine such questions as polarity fluctuations at large scale needs to solve the fully non-linear problem. Work on this later step is now in progress for incompressible flows and an account of it will also be given.

Axially symmetric flows seems the easier to achieve practically among all flows which are kinematically feasible in a cylindrical container. Three families of such flows will be compared:

(i) helical dynamos are obtained with flows such that the azimuthal and axial components depend of the radial distance only. The main features of such dynamos have been studied for example by Ruzmaikin, Sokoloff and Shukurov in the limit of large magnetic Reynolds numbers (JFM, 1988, 197, 39) and by Lupian and Shukurov in the critical regime (Magnit. Gidrod.1992, n°3, 29)

(ii) purely azimuthal flows : a dynamo effect is obtained with a flow reduced to a single component if the azimuthal velocity depends of radial <u>and</u> axial coordinates .

(iii) more general 3 dimensional flows depending on coordinates r, z, including also flows with a given time dependence in order to modelize the influence of a finite correlation time of the velocity on the critical magnetic Reynolds number.

The role of the small scales of the flow is examined. It is shown that critical magnetic Reynolds numbers (based on cylinder radius and maximal flow speed) smaller than ten may be obtained using for example toroidal cells with radial width equal to about 1/10 of the radius and axial length equal also to 1/10 of the axial period.

FINITE ELEMENT MODELISATION AND SIMULATION OF KINEMATIC DYNAMO EFFECT

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Part 1: Numerical analysis.

The objective of this work is to simulate kinematic dynamo effect in an eventual geometric complex domain, without any restrictive hypothesis on induction field neither on the material properties (electrical conductivity and magnetic permeability). Equations of kinematic dynamo effect are modelised, apply ingfinite element description in the 3D-space plus first order finite difference algorithm in time.

Two main formulations are derived: one is depending on electric and magnetic potentials, the other one is depending on induction field only. The choice offormulation is settled first by the distribution of magnetic permeability (continuous or not in all the domain) and second by the size of the geometric domain. Precision on magnetic energy growth and conditions at the fronteer are then deduced from this choice. The two formulations lead to the same resolution algorithm: Iterative Cholesky Conjugate Gradients on diffusive and transitory terms, plus iterative algorithm on convective terms.

Part 2: Application to a screw motion.

Simulation results obtained for a given screw body motion are presented.When helicity is infinite, critical magnetic Reynolds number is evaluated and compared to previous analytical results. Induction field, current density, Lorentz forces and magnetic energy density distributions are presented in the 3D domain. Influence of finite helicity (axial end effects) on the critical magnetic Reynolds number is evaluated. Other simulations intend to bring new informations for ulterior experiments.

ANOMALY MAGNETIC DIFFUSION IN A THIN DISC DYNAMO PROBLEM

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We consider magnetic field generation in a thin differential rotating disk with a turbulent flow of electrically conductive liquid. This problem is important e.g. for galactic dynamo theory because galaxies can be considered as thin disks with aspect ratio λ of order 10^{-2}. An asymptotic expansion of mean-field electrodynamics equations in respect to the small parameter λ can be developed. This expansion is based on the fact, that the diffusion time scale across the thin disk is much less than that one along this disk. A version ofexpansion mentioned above has been suggested by Ruzmaikin *et al.*, 1988. This expansion takes into account local magnetic field generation and its diffusion transport along the disk. A.Soward,1992 pointed out another physical process to be taken into account in the correct thin disk asymptotic expansion. It is atransport of locally generated magnetic field through the vacuum surrounding the thin disk under consideration.

We demonstrate, that the process considered by A.Soward can be described as an anomaly diffusion of locally generated magnetic field along the disk. Let us remember, that adisplacement of a particle involved into an usual diffusion is proportional to $t^{1/2}$, while that one of a particle involved into an anomaly diffusion is proportional to t^{μ} where μ is a constant different from 1/2. From the mathematical point of view anomaly diffusion can be presented with a help of integral operator.

We compare properties of an asymptotic expansion which includes a term with anomaly diffusion with corresponding results of expansion suggested by Ruzmaikin *et al.* It is shown that the term with anomaly diffusion can be even more important then that one responsible for the usual magnetic field diffusion. In this sense the process suggested by A.Soward is important to get a correct asymptotical expansion of the thin disk dynamo problem.

Applications of thin disk dynamo problem to description of magnetic field generation in a given galaxy should be based on some observational information of the galaxy hydrodynamics (rotation curve etc). We demonstrate that the real uncertainties in this information are as a rule more important then the roles of anomaly as well as that one of usual diffusion in expansions under consideration. It is why dynamo models presented by Ruzmaikin *et al.* can be considered as a reasonable approximation to corresponding solutions of dynamo equations.

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THE CORRELATION ANALYSIS OF THE SECULAR VARIATION

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The secular variation with period of 100 years is considered as a random process. The statistical approach of its investigation is proposed. The statistical properties of the space distribution of the secular variation field are discussed. To discribe the basic properties of a such process we construct the correlation functions for all three components of the secular variation field. We study the propagation of theese functions through the mantle to the liquid core of the Earth. We emphasize that the method proposed is more regular then the extrapolation to the Earth's core of the field itself. Two problem are solved. Firstly, we find the correlation functions of the fluctuative dynamo model at the surface of the Earth liquid core and show that its main properties come to an agreement with the observations on 1980 epoch. Secondly, we solve the inverse problem, when we find the correlation functions at the Earth's core using the observed dates at the Earth's surface. So as the inverse problem is ill-poison we find exact solution for correlation functions at the core-mantle boundary. The methods of regularization are used. We found that the correlation scale of the random magnetic field structures at the surface of the liqiud core is equal to 800 km. From the point of view of the theory of the fluctuative dynamo resultes obtained may be used for determining of the magnetic Reynolds number.

Section B.
FERROFLUIDS

Hydrodynamics

COMPUTATIONAL ANALYSIS OF FREE SURFACE MAGNETOHYDROSTATIC EQUILIBRIA: FORCE VERSUS ENERGY FORMULATION

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The governing equations of static equilibrium of free surfaces of ferrofluids in external magnetic field are derived from either a force formulation or an energy formulation. The former amounts to force balancing and accounts for magnetostatic force, gravitational force and capillary force; it yields Laplace's equation for the magnetostatic potential inside the ferrofluid and the surrounding non-magnetic medium, the Young-Laplace equation for the shape of the free ferrofluid surface and an integral constraint stemming from the incompressibility of the ferrofluid [1]. The latter amounts to minimizing the total energy of the ferrofluid and its non-magnetic surroundings with respect to all disturbances of magnetostatic potential and free surface shape that preserve the ferrofluid volume in any free surface deformation. Force and energy formulations are equivalent in the continuum; that is, the equations of force formulation are the necessary conditions for energy minimization.

The governing equations in either formulation give rise to a nonlinear, free boundary problem because the free surface shape enters the equations nonlinearly through its curvature and it is unknown a priori. Therefore, interface shape and magnetostatic potential must be solved for simultaneously at different values of the applied field strength, H_0. The equations are discretized by a combination of Galerkin's method of weighted residuals and the finite element method. The resulting set of nonlinear algebraic equations is, in compact form,

force formulation $\quad \underline{R}(\underline{u},\underline{h},K;H_0) = \underline{0}$ (1)

energy formulation $\quad \delta\underline{\wp}(\underline{u},\underline{h},K;H_0) = \underline{0}$ (2)

where: $\underline{R}$ is the set of residuals of the equations and $\delta\underline{\wp}$ is the first variation of the energy functional; $\underline{u}$ and $\underline{h}$ are the sets of unknown values of the magnetostatic potential and of the free surface displacement at the nodes of the discretization, respectively; K is a reference pressure along the free surface in the force formulation and a Lagrange multiplier associated with the constant volume constraint in the energy formulation.

The systems (1) and (2) are solved iteratively by Newton-Raphson method; the iteration scheme in the force and energy formulation is, respectively,

$$\underline{\underline{J}}^{(k)}\underline{d}^{(k)} = -\underline{R}^{(k)} \text{ and } \underline{\underline{H}}^{(k)}\underline{d}^{(k)} = -\delta\underline{\wp}^{(k)}$$

where: k is the iteration counter and $\underline{d}^{(k)} \equiv \underline{x}^{(k+1)} - \underline{x}^{(k)}$ is the update of the solution $\underline{x} \equiv [\underline{u},\underline{h},K]$. $\underline{\underline{J}}^{(k)}$ is the Jacobian matrix of equations (1) and $\underline{\underline{H}}^{(k)}$ is the Jacobian matrix of equations (2) (the so-called Hessian or stability matrix), evaluated at $\underline{x} = \underline{x}^{(k)}$.

Although force and energy formulations are equivalent in the continuum, their discrete versions (1) and (2) are not. The difference originates from $\underline{\underline{J}}$ and $\underline{\underline{H}}$: $\underline{\underline{J}}$ is non-symmetric whereas $\underline{\underline{H}}$ is symmetric [2]. As a result, the structure of the solution space of force and of energy formulations are different. Computations show that the dependence of equilibrium solutions on H_0 is not identical in the two formulations, especially in regard to their bifurcation and stability. The difference between solution spaces of each formulation hightens with increasing H_0 and it persists against discretization refinement.

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MAGNETIC FLUID STRIPES AS A MACROSCOPIC BIDIMENSIONAL SMECTIC

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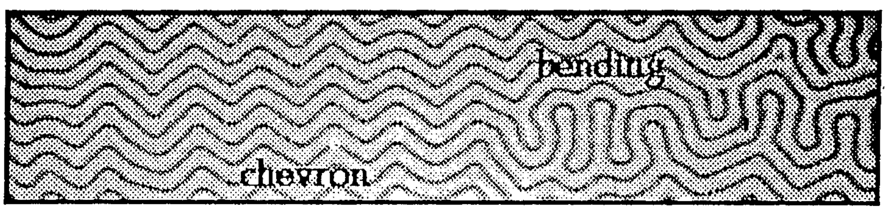
A droplet of magnetic fluid in an Hele-Shaw cell under a perpendicular magnetic field H forms different patterns like stripe(s) or complicated labyrinthine structures.

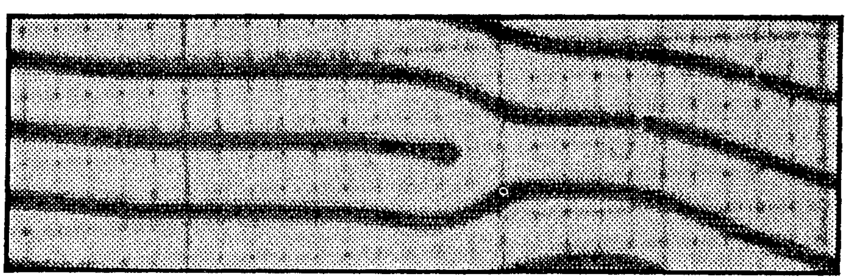
Two-dimensional smectic-like structures are obtained with many parallel stripes. The period is typically a few millimeters. Like in a mesomorphous smectic we can observe deformations of the layers : both chevron ('zig-zag') and bending patterns are obtained at a threshold value of $H = H_C$ (picture 1). The threshold also depends on the stripe thickness d : H_C increases when d decreases. The first deformation is a collective phenomenon whereas bending occurs on an isolated stripe. Compression and curvature moduli of the stripes B and K, are measured from very simple experiments. An analogy with a bidimensional smectic allows us to obtain predictions for B and K as functions of H and d. Results are discussed.

Many defects like edge dislocations are also observed (picture 2). The deformation profile around the defect gives us a value of the ratio K/B.

Finally, similarities with other two-dimensional systems, like amphiphile monolayers and ferro-magnetic films, in which there is also competition between attractive short-range interactions and repulsive long-range interactions (dipolar interactions), are presented.



Picture 1 : chevron and bending patterns are obtained at the same threshold value of the magnetic field in the same system (the period of the layers is roughly 3 mm).



Picture 2 : edge dislocation with a unit Burger's vector (the period of the layers is roughly 2 mm)

DYNAMICS OF A 2D MAGNETIC FLUID DROPLET IN A TIME-AVERAGED ROTATING MAGNETIC FIELD

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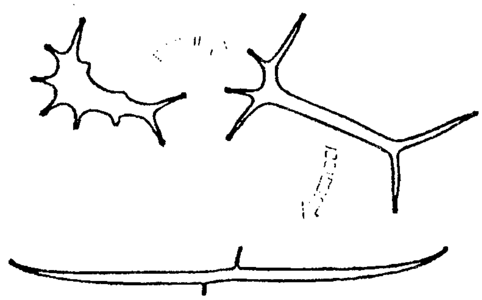
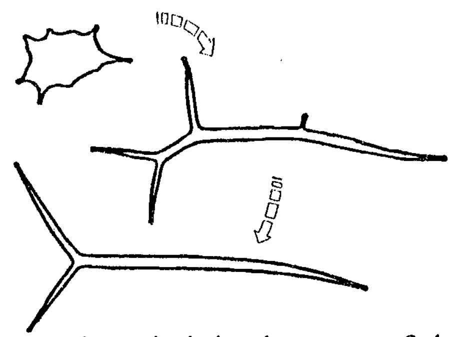
An experimental study of a magnetic fluid (MF) microdrop in a rotating magnetic field shows a wide variety of complex phenomena [1]. The complete theoretical explanation is yet absent. A linear small perturbation analysis gives us magnetic field threshold values in respect to n-lobe perturbations [2]. It is important to know if n-lobe shapes exist as stable or metastable configurations. To prove it we simulate numerically the behaviour of a MF droplet in 2D. Neglecting inertia terms in the Navier-Stokes equation one can use boundary integral equations [3] to describe creeping flow with a free boundary. At high-frequencies only time-averaged surface force have to be considered.

a)



b)



Two numerical simulations, shown in Figure, represent dynamical developments of the droplet shape from two different arbitrary initial shapes. Final shapes show that both 2-spike and 3-spike configurations can exist in time intervals, which are longer than the characteristic transition time. In the other simulation symmetric 3-spike shape is obtained, starting from a symmetric and more favourable initial state. A decrease of the magnetic field below the 3-spike threshold [2] have caused slow transition to 2-spike shape. These results are in good agreement with the energy minimum calculations, carried out in [4].

This work was supported by "Le Réseau Formation Recherche n°90R0933 du Ministère de l'Enseignement Superieur et de la Recherche" of France. Two of us (A.Cēbers, S.Lācis) are thankful to International Science Foundation for financial support of the research in terms of long-time grant LBG000.

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A NUMERICAL STUDY OF THE EVOLUTION OF QUASI-TWO-DIMENSIONAL MAGNETIC FLUID SHAPE

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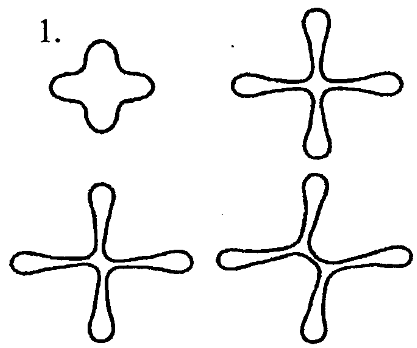
Remarkable labyrinthine patterns are formed when a domain of magnetic fluid is trapped between two horizontal glass plates in a vertical magnetic field. Here are presented the numerical simulation results of the magnetic fluid droplet long-time behavior.

The free boundary problem for the interface motion is studied numerically using boundary integral equation technique[1,2]. Following the standard approach of the Hele-Shaw problem we use Darcy approximation for magnetic fluid. To find magnetic term we assume that magnetization of the drop is uniform and demagnetization field is derived from magnetostatistic potential of fictios magnetic charge density. Expressing stream function as single layer potential boundary integral formulation of the problem is obtained. In nondimensional variables

1.

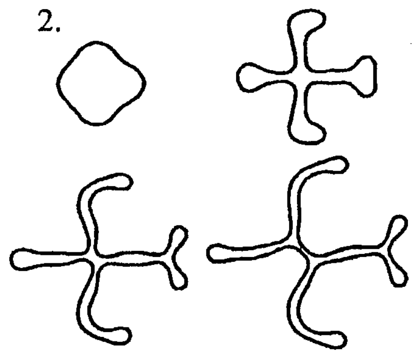


$$V_x = \frac{\partial \varphi}{\partial y}, V_y = -\frac{\partial \varphi}{\partial x}, \varphi = \frac{1}{2\pi}\oint f(s') \ln\left|\vec{R}(s') - \vec{R}\right| ds'$$

$$f = -2\frac{\partial p}{\partial s} + \frac{1}{\pi}\oint f(s') \frac{\partial}{\partial n} \ln\left|\vec{R}(s') - \vec{R}(s)\right| ds'$$

$$p = k + \frac{Bm}{h^2}\oint x'_s \ln \frac{(y - y') + \left|\vec{R}(s) - \vec{R}(s)\right|}{(y - y') + \sqrt{\left(\vec{R}(s) - \vec{R}(s)\right)^2 + h^2}} ds',$$

2.



where $\vec{R}(s)$ is parametric equation of interface, h is distance between plates, k is the curvature and Bm is magnetic Bond number.

The boundary integral equation is solved using Galerkin's method. New location of the boundary is found by Eyler's method.

The numerical simulation result show that fourfold vertice is unstable and divides in two threefold triangular vertices. Chracteristic energies during the dynamics of those topological changes are calculated.

Figure 1. Bm=40, h=2, t=0, 0.18, 0.25, 0.36; Figure 2. Bm=21, h=1, t=0, 0.07, 0.15, 0.26.

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MOTION OF A NONMAGNETIC PARTICLE IN A FERROFLUIDIC DENSITY SPECTROMETER WITH AN AIR GAP IN THE SHAPE OF A WEDGE

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On a spherical nonmagnetic particle of radius R, volume V and density ρ_S, moving slowly with the velocity $\vec{v}$ in an incompressible, nonpolarizable and nonconducting ferrofluid of density ρ_F, dynamic viscosity η and magnetic susceptibility χ_F, introduced into the magnetic field $\vec{H}$ of an electromagnet with an air gap in the shape of a wedge, act the apparent weight $\vec{F}_1=(\rho_S-\rho_F)\vec{g}V$, the Stokes friction force $\vec{F}_2=-6\pi\eta R\vec{v}$ and the magnetic force $\vec{F}_3=-\mu_0\chi_F H\nabla H$.

In cylindrical coordinates r, φ ,z (with Oz-axis coinciding with the edge of the wedge) the differential equations of motion take the form

$$\ddot{r}-r\dot{\varphi}^2=\frac{\rho_S-\rho_F}{\rho_S}g\sin\theta\cos\varphi-\frac{9\eta}{2R^2\rho_S}\dot{r}+\frac{\mu_0\chi_F H_m^2 r_m^2}{\rho_S}\frac{1}{r^3}, \tag{1}$$

$$2\dot{r}\dot{\varphi}+r\ddot{\varphi}=\frac{\rho_S-\rho_F}{\rho_S}g\sin\theta\sin\varphi-\frac{9\eta}{2R^2\rho_S}r\dot{\varphi}, \tag{2}$$

$$\ddot{z}=\frac{\rho_S-\rho_F}{\rho_S}g\cos\theta-\frac{9\eta}{2R^2\rho_S}\dot{z}, \tag{3}$$

where $\pi-\theta$ is the angle between the Oz-axis and the vertical direction, r_m - the polar radius of the middle of the wedge and $H_m=H(r_m)$.

A solution of the equation (2) is $\varphi=0$.

The solution of the equation (3) with the initial conditions $z(0)=z_0$ and $\dot{z}(0)=0$ has the form

$$z=z_0+\frac{2R^2(\rho_S-\rho_F)g\cos\theta}{9\eta}\left[\frac{2R^2\rho_S}{9\eta}\left(e^{-\frac{9\eta}{2R^2\rho_S}t}-1\right)+t\right].$$

The equation (1) may be integrated exactly only in certain cases. The solutions satisfying the initial conditions $r(0)=r_0$ and $\dot{r}(0)=0$ are:

a) $t<\frac{2R^2\rho_S}{9\eta}$: the solution is expressed by elliptic integrals; if

$$r<\left|\left(\frac{\mu_0\chi_F H_m^2 r_m^2}{(\rho_S-\rho_F)g\sin\theta}\right)^{1/3}\right|,\ \text{then}\ r^2=r_0^2+\frac{\mu_0\chi_F H_m^2 r_m^2}{\rho_S r_0^2}t^2;$$

b) $$r>\left|\left(\frac{\mu_0\chi_F H_m^2 r_m^2}{(\rho_S-\rho_F)g\sin\theta}\right)^{1/3}\right|\ :\ r=r_0+\frac{2R^2(\rho_S-\rho_F)g\sin\theta}{9\eta}\left[\frac{2R^2\rho_S}{9\eta}\left(e^{-\frac{9\eta}{2R^2\rho_S}t}-1\right)+t\right].$$

In other cases the solution is determined by methods of approximate integration.

EFFECT OF MAGNETIC FIELD ON OSCILLATING MOTION OF PISTON IMMERSED IN A MAGNETIC FLUID

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Theoretical and experimental studies are carried out to clarify the effect of transverse magnetic field on the oscillation of piston immersed in a magnetic fluid as the basic study for the development of a magnetic fluid viscous damper by using a simplified model as shown in Fig.1.

The oscillating amplitude ratio of piston (Δz) to outer cylinder (Δa) is expressed as follows.

$$\frac{\Delta z}{\Delta a}=\left\{\frac{1+\left(\frac{2\zeta\omega}{p}\right)^2}{\left\{1-\left(\frac{\omega}{p}\right)^2\right\}^2+\left(\frac{2\zeta\omega}{p}\right)^2}\right\}^{\frac{1}{2}}$$

where ω is angular frequency of oscillation, $\zeta=\mu/p$, $\mu=C/2(m'+m_A)$, $p=\{k/(m'+m_A)\}^{\frac{1}{2}}$: natural frequency, C : viscous damping coefficient, k : spring constant, m_A : added mass, m' : mass of piston and weight.

Figure 2 shows the experimental results of the frequency response curve of the oscillation of piston compared with the analytical results.

It is shown that the relative amplitude ($\Delta a-\Delta z$) of piston to the outer cylinder decreases with application of magnetic field which indicates the viscous damping effect of magnetic field on the oscillation of piston relative to the outer cylinder.

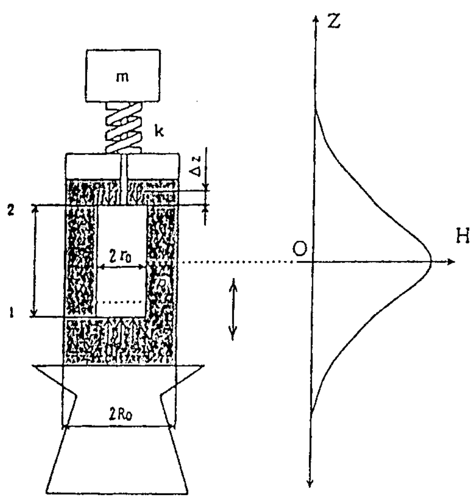

Fig.1 Analytical model of viscous damper

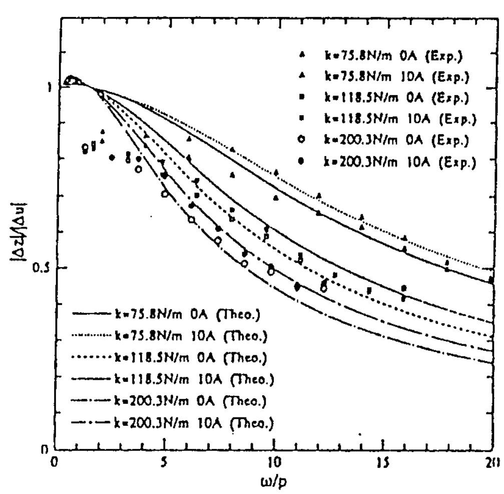

Fig.2 Frequency response curve with $m=75.46$g

DYNAMICS OF VORTEX STRUCTURES IN MAGNETIC FLUIDS

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Study of magnetic fluids in rotating magnetic fields goes back to the paper [1] and the interest to the problem mentioned does not slacken up to the present time. The effects of dynamic structuring of ferrocolloid flat layers forming microvortices, which were predicted theoretically in [2] and confirmed experimentally in [3], are the least studied ones.

The present paper shows the experimental results of flat layers structuring study in magnetic fluids of two type (a) magnetite in kerosene diluted with oil, (b) the same as (a) but diluted with rubber solution in kerosene. The rotating field (H_m=100 Oe, angular velocity Ω= 75 rad/s) was produced by two permanent magnets having been fixed on motor-driven whirligig. The image from a microscope was transfered by videocamera to monitor and then recorded on a computer-ganded VCR.

1. The layer of magnetic fluid falls apart in rotating field into numerous microvortices being the local aggregations of particles rotating in the same direction as H_m, but with much lower angular velocity. The obtained results, concerning the stage mentioned above, agree well with theory [2] and experiment [3]. However, increasing of colloid viscosity due to the oil presence change the relaxational characteristics of the process. At a fixed field rotation velocity the number of vortices n was decreased with time t, while their sizes d were increased. The Fig.1 shows the dependences $n(t)$ and $d(t)$ for a part of a sample being 50×40 μm in size. The initial value n =1125 was falling down by the order during the first minute, was equal to five by the 12th minute and became stable at last. The change of vortices diameter occurs in the reverse order and is arrested after reaching 6-10 μm in size. The increasing of d comes about by two ways.The microvortices are increased (1) at the expence of capturing of free particles from the surrounding colloid; (2) at the expence of coalescence. The Fig.2 shows the dynamics of the coalescence process of two vortices.

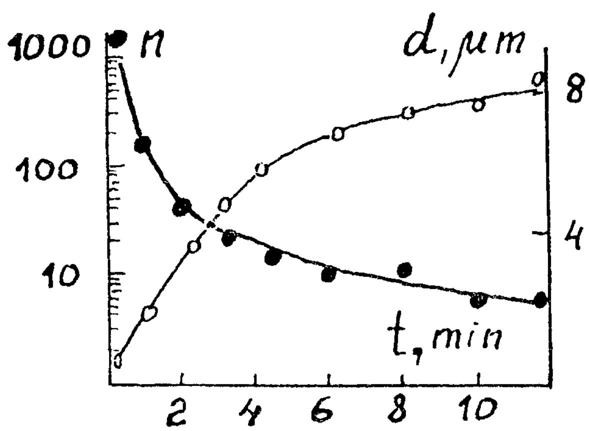

Fig.1. Dependence of the vortices number (●) and their sizes (O) on time.

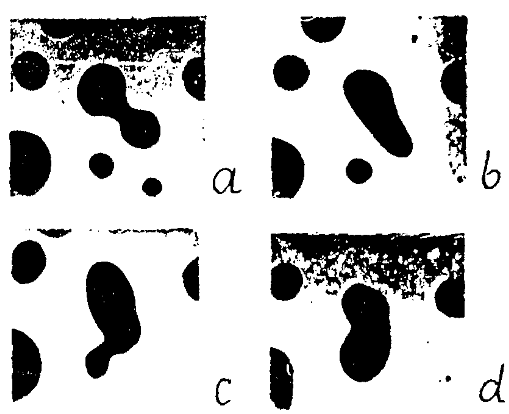

Fig.2. The sequential stages of the vortices coalescence.

Since both aggregates rotate at the same direction, then rigid catching happens under contact, and one of the aggregate seems to turn for another. Such mechanism of vortices coalescence agrees with predictions on circular magnetic ordering of magnetic moments of particles in vortices [4]. The whole process takes 5-10 seconds and the diameter of new aggregate is 25-30% as large as each of initial ones. This value is inversely dependent on Δd of initial vortices.

2. Due to the effect of displaced floculation the magnetic fluid in solution of rubber in kerosene is a blend of two colloids having different concentration of ferroparticles. Its behaviour in H_m differs strongly from that cited in part 1 of the present paper and in [3]. In rotating field the regions concentrated with particles move slowly around the center of masses changing gradually their form and keeping clear phase separation boundary. Under the additional effect to the considered system with a stationary constant magnetic field H_0 the wave instability is evolved. The state of instability is increased with H_0 growth. The crests are formed, curled along the direction of H_m rotation. Further the microvortices are generated in concentrated phase volume the number of which is also increased with H_0, the phase separation boundary breaks down, and the vortices move intensively along the region boundary in the direction of field rotation. The Fig.3 shows the sequential stages of the structural layer changes in $H_m + H_0$.

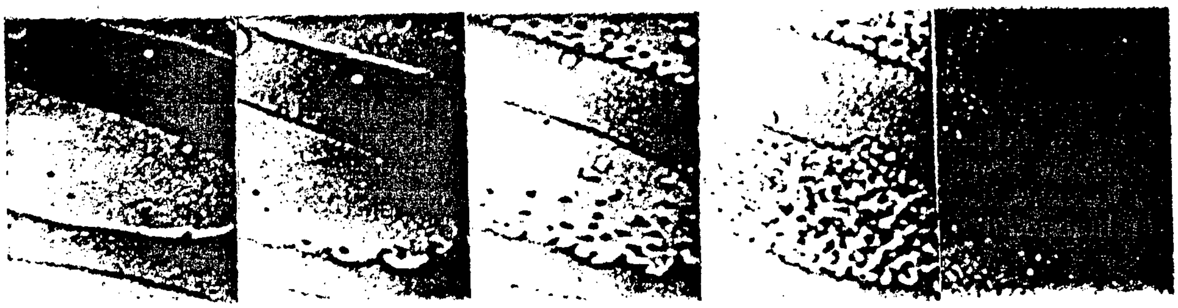

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Fig.3. Changes of the layer structure in $H_m + H_0$ under the change of H_0 from 0 to 100 Oe. H_m = const.

Presently, the theory of the effect is not still developed but, obviously, its more detailed study will help to understand better some natural phenomena in micro- and macroworld the base of which are the process of self-organisation.

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STRUCTURING OF NON-MAGNETIC MICROSPHERES IN FERROCOLLOID FLAT LAYER IN ROTATING MAGNETIC FIELD

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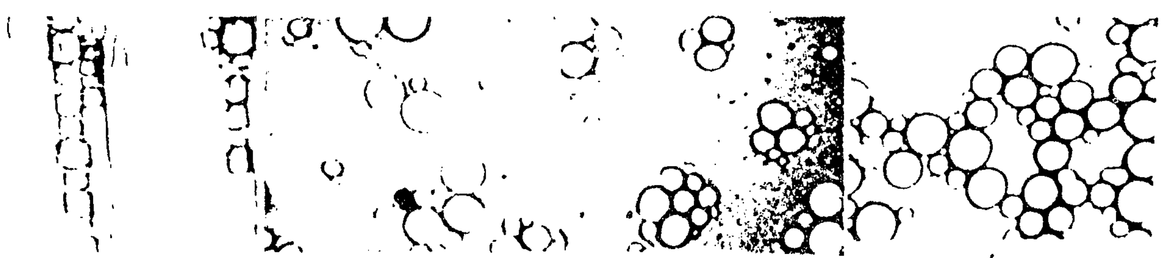
Injection of non-magnetic particles ("magnetic holes") into magnetic fluids is equivalent to forming of "diamagnetic" particles having magnetization oppositely-directed to that of the surrounding fluid. Magnetic interaction of the "holes", which is considered in the first approximation to be magneto-dipole, determines possibility of dispersion structures appearance in applied fields. Such systems are a kind of special interest through possibility to control the particle interaction parameters with magnetic field and to use them as a model for some physical processes.

It was shown in [1,2] that under the change of magnetic field orientation from lateral layer boundary to longitudinal one the character of particle interaction is changed from repelling to their attraction along the applied field direction, i.e., similar to behaiour of magnetic particles in magnetic fluid. It is clear that the system will show the same behaviour in alternating magnetic field. It is known, however, that a magnetic field layer falls apart in rotating magnetic field into discrete regions—microvortices—moving around their exes [3].

The paper shows the experimental modelling results of vortice structures in flat layers of magnetic fluids using the two-dimensional system of non-magnetic microspheres. Under the immovable field the microspheres form the chains parallel to the field vector of a chain as in [1]. If the field rotates then the chains break down into small aggregates and separate particles moving in the same directions as applied field but with smaller velocity. Eventually the growth of aggregates is observed at the expense of joining of free particles and coalescence with another aggregates. The figure below shows the process kinetics.



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As an aggregate is increasing its rotation velocity falls off to zero. In the presence of immovable bias field the block mobility of separate parts of large-sized aggregates relatively to each other is observed. Some questions related to the mechanism of realization of rotating non-magnetic microspheres and their components as well as adequacy of the model obtained to the real effects in magnetic fluids is under discussion.

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EQUATION OF MOTION OF 2D ELLIPTIC MAGNETIC FLUID DROPLET IN A ROTATING MAGNETIC FIELD

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It is well-known that for rigid magnetic dipole there is a critical angular velocity of a rotating field low which rotations of a particle and field are synchronized [1]. Similar phenomena are observed for bound pair of soft magnetic particles [2,3]. The magnetic fluid (MF) microdroplet in the rotating agnetic field includes a wide variety of very complex phenomena in the high-frequency range [4].

The scope of the present paper is to derive simple equations of motion for a 2D MF droplet under sumption of an elliptic shape of it. A small size of microdroplets and relatively small characteristic locities of flows allows to neglect inertia and gravity terms, concentrating on surface tension and agnetic forces on the surface of the droplet. Hence the motion of a free surface of a droplet is scribed as a 2D creeping flow. Motion of a MF droplet is described by the length a of its large semi-is and the angle ϑ between it and a direction of X-axis of the laboratory coordinates. In comparison the earlier version [5] shear stresses of flow for arbitrary viscosities of both fluids are taken into count. For that the creeping flow outside the droplet is treated exactly [6], the flow inside the droplet approximated by constant gradients γ_{ik} of velocity field $v_i = \gamma_{ik} x_k$. To derive equations of motion the rial technique [7] is applied. Obtained motion equations are the following:

$$\dot{a} = \frac{2a^2}{\pi\left(a^2+1+2\lambda a^2\right)}\left[\frac{(\mu-1)^2}{16} Bm\,a\left(\frac{\cos^2\vartheta}{(a^2+\mu)^2} - \frac{\sin^2\vartheta}{(\mu a^2+1)^2}\right) - \frac{\Phi(a)}{a^4-1}\right],$$

$$\Phi(a) = \left((a^4+1)\,\mathrm{E}(e) - 2\,\mathrm{K}(e)\right), \lambda = \eta_{in}/\eta_{ex}, \; a = a_{\dim}/R$$

$$\dot{\vartheta} = \Omega_H - \Omega_{cr}\sin 2\vartheta, \quad \text{where } \Omega_{cr} = \frac{Bm}{16\pi}\frac{(\mu-1)^2 a^2}{\left(a^2+\mu\right)\left(a^2\mu+1\right)}\frac{2a^2\dfrac{a^4+1}{a^4-1} + \lambda\left(a^4-1\right)}{2a^2+\lambda\left(a^4+1\right)}$$

here $\mathrm{E}(e), \mathrm{K}(e)$ are the complete elliptic integrals, $e^2 = 1 - a^2/b^2$, η_{in}, η_{ex}: viscosities of fluid inside, sp., outside the droplet, H_0: magnetic field amplitude, R: a radius of a circular drop shape, Ω_H: an igular frequency of a magnetic field rotation. A time scaling unit is $\tau_b = R\eta_{ex}/\sigma$.

Results of numerical simulation, applying Runge-Kutta 4th order algorithm show that in comparison ith equations of motion considered in [5], the better agreement with 2D BEM simulation results is otained. It means that besides the elongational and rotational motions of the droplet shear, especially ear the critical frequency, is important.

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A MAGNETIC BODY IMMERSED IN A MAGNETIC FLUID FILLED IN A SPHERICAL VESSEL

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For the first time, buoyancy and stable levitation of a magnetic body (magnet) immersed in a magnetic fluid filled in any vessel was observed by R.E.Rosensweig [1]. A force that act on a magnet may be obtained by numerically calculation. The analitical formula for the force was turned out by A.O.Cebers [2] for a cylindrical magnet in a cylindrical vessel with a magnetic fluid. In the present report the analytical solution for a magnet immersed in a magnetic fluid filled in a spherical vessel was obtained.

Let us consider that a magnet immersed in a homogeneous uncompressible magnetic fluid which fills in a closed vessel. A magnetic permeability of the fluid μ and a magnetization of a magnet substance M_m are homogeneous type, $\mu = const., M_m = const.$ Magnetization of the magnetic fluid M ($4\pi \boldsymbol{M} = \mu \boldsymbol{H} - \boldsymbol{H}$) is small, $4\pi M \ll H$, here $\boldsymbol{H}$ is a magnetic field in the fluid.

Under this conditions, a force that act on a magnet is calculated by the following formula (here S_1 is a vessel surface, $\boldsymbol{H}_0$ is a magnetic field in absence of a magnetic fluid):

$$F_{mi} = -\frac{\mu - 1}{8\pi} \int\limits_{S_1} H_0^2 n_i dS\,, \ \boldsymbol{H}_0 = \nabla \phi_0 \tag{1}$$

In absence of the magnetic fluid a magnetic field of a magnet $\boldsymbol{H}_0$ is the field of a magnetic dipole for enough large radius-vector $\boldsymbol{r}$,

$$\boldsymbol{H}_0 = \nabla \phi_0\,, \ \phi_0 = (\boldsymbol{m} \cdot \boldsymbol{r})/r^3\,, \tag{2}$$

for $r > r_m$. Here $\boldsymbol{r}$ is radius-vector of the Cartesian frame x, y, z, origin of this frame is the centre of a magnet O, $\boldsymbol{m}$ - a magnet moment, $m = V_m M_m$, V_m is a volume of the magnet.

Let us consider that $\boldsymbol{m}$ directs along axis x, the vessel form is a sphere with the radius R and the centre O'. The vector $\boldsymbol{r}_0$ joins the points O' and O, $\boldsymbol{r}_0 = (a, b, c)$, $r_0 \ll R$, $|R - r_0| > r_m$. Under this conditions, using equations (1) and (2) the force $\boldsymbol{F}$ that act on a magnet is calculated

$$F_x = -\frac{4}{3} K a\,, \ F_y = -K b\,, \ F_z = -K c\,, \ K = 9(\mu - 1) m^2 / 5R^5\,. \tag{3}$$

The solution obtained shows that the force $\boldsymbol{F}$ and replacement vector $\boldsymbol{r}_0$ have't the same director. The director of the force is determined by vector $\boldsymbol{m}$. The value of the force does't depend up a magnet form and a magnetic field near a magnet when the vessel is enough large and replacement vector is enough small. The formula (3) may be used for the projecting of the vibration pickups based the magnetic fluids.

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NONISOTHERMAL MAGNETIC FLUID IN ROTATING MAGNETIC FIELD

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Circulation flows of dielectric magnetic fluid in rotating magnetic field have been the subject of many investigations pioneered by R. Moskovitz and R. E. Rosensweig [1]. Such motion are caused by volumetric and surface forces arising in magnetic fluids due to space nonuniformity of magnetic susceptibility and its nonequilibrium character (the relaxation time of magnetization is comparable with the period of field rotation). In the case of weak fields and low frequencies dissipation of energy is weak, the fluid is uniform and volume forces are unessential. The major part is plaid by the surface effects. As the frequency (or amplitude) of the field increase , the situation changed qualitatively: nonuniformity of the temperature and magnetic field is responsible for generating in fluid the volumetric magnetic forces.

In the present study the problem of nonisothemal fluid flow has been solved analytically. A circular vertical cylinder of a length much larger than its diameter was filled with magnetic fluid. The rotating magnetic field, being uniform far from cylinder, was oriented normal to its axis. The problem has been solved on the basis of ferrohydrodynamics equations [2] allowing for magnetization nonequilibrium. The field is considered weak in the sense that the fluid magnetization M is proportional to the field intensity H. This assumption does not mean that heat release can be ignored, as the field frequency may be rather high and proportionality between M and H in real ferrocolloids is retained up to H ~ 1 kA/m. Another impotent assumption is that of weak vorticity, i.e. is considered small in comparison with the rotating field frequency ω. This condition is well performed in practice and allows the magnetic part of problem to be solved regardless of the hydrodynamical one. Further more, allowances are made for the fact that the characteristic temperature differences in fluid are small in comparison with the absolute temperature. Therefore, the temperature dependence of susceptibility can be approximated by the linear low.

In view of the above suggestions, the ferrohydrodynamics equations allows an exact solution with cubic velocity profile

$$V(r) = \frac{\omega\varepsilon\, [\, \mu_0\, \chi_2\, H_0^2\,]^2\, r\, (\, R^2 - r^2\,)}{2\, \eta\, \kappa\, [\, 4 + 4\, \chi_1 + \chi^2\,]^{2}} \qquad (1)$$

where χ_1 and χ_2 are the real and imaginary parts of dynamic susceptibility, R is the cylinder radius, κ, η are coefficients of heat conductivity and dynamic viscosity, ε is the temperature coefficient of tangent of loss angle (tg δ). Note, that tg δ decreases with the temperature and ε is negative. This means that the fluid motion is opposite to the field rotation as revealed experimentally. The comparison of velocity amplitude from (1) with experimental data shows a good agreement.

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HYDRODYNAMIC INVESTIGATION ON ELECTRORHEOLOGY OF A COLLOIDAL ELECTRO-RHEOLOGICAL FLUID

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Many study of electro-rheological fluid (ER fluid) have been made for a long time. e ER fluids are sorted out two types on the constitution of particles, so colloidal fluid d liquid crystal. They, however, have many problems for the application to engineering stems. The fluids are required the large apparent viscosity in an electric field, the small cosity in no applying electric field and the stability of dispersion of particles. On the ner hand, hydrodynamic constitutive equations of an ER fluid have not been nstructed theoretically enough to explain the experimental data because they have ade study of the ER fluids with focus on electric characteristics principally. In addition the theory, the effect of aggregation of particles of the ER fluid on the hydrodynamic aractristics must be also considered in an electric field.

In our this investigation, hydrodynamic constitutive equations of an ER fluid of lloidal fluid type with taking into account internal angular momentum of particles and gregation of the particles are suggested. Model of the aggregation in an electric field that ape of the aggregation is approximated by prolate spheroid is conducted. The eoretical results are compared with experimental data of electrorheological aracteristics, so apparent viscosity of the ER fluid.

NONEQUILIBRIUM THEORY OF MAGNETIC FLUID WITH FROZEN MAGNETIZATION

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The new complete set of equations for magnetic fluid with frozen magnetization was derived using the principle of virtual work and Onsager's theorem. The system of equations is as follows

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_j)}{\partial x_j} = 0$$

$$\rho\frac{\partial v_i}{\partial t} + \rho v_j \frac{\partial v_i}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \left(H_i^{eff} - H_i\right)\frac{\partial(\rho\mu_j)}{\partial x_j} + \rho\mu_j\frac{\partial H_i^{eff}}{\partial x_j} + (\eta + \eta_r)\nabla^2 v_i +$$
$$+\left(\zeta + \frac{\eta}{3} - \eta_r\right)\frac{\partial}{\partial x_i}\left(\frac{\partial v_k}{\partial x_k}\right); \qquad P = \rho^2\frac{\partial u}{\partial \rho};$$

$$T\left[\frac{\partial(\rho s)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho s v_j - \frac{\chi}{T}\frac{\partial T}{\partial x_j}\right)\right] = \frac{\chi}{T}(\nabla T)^2 + \zeta\left(\frac{\partial v_k}{\partial x_k}\right)^2 + \frac{\eta}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\frac{\partial v_k}{\partial x_k}\delta_{ij}\right)^2 +$$
$$+\frac{\eta_r}{2}\left(\frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i}\right)^2 + \frac{1}{\tau}\left(\vec{H} - \vec{H}^{eff}\right)^2; \quad T = \frac{\partial u}{\partial s}\ ; \quad H_i^{eff} = \frac{\partial u}{\partial \mu_i};$$

$$\frac{d\mu_i}{dt} = \mu_j\frac{\partial v_i}{\partial x_j} + \frac{1}{\rho\tau}\left(H_i - H_i^{eff}\right); \; H_i = -\frac{\partial \Psi}{\partial x_i}; \quad \nabla^2\Psi = -4\pi\frac{\partial(\rho\mu_i)}{\partial x_i},$$

We assume the specific internal energy u of magnetic fluid to be a function of density ρ, the specific entropy s and the components of the vector of specific magnetization μ_i. P is the pressure in the absence of the magnetic field; ζ, η, η_r are the coefficients of bulk viscosity, shear viscosity, vortex viscosity, respectively and χ is the thermal conductivity.

MAGNETIC FLUID SLOSHING IN MOVING CONTAINER

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Introduction

Liquid sloshing can be excited by a variety of motions of the liquid container, and he importance of liquid sloshing on the space technology and the seismology is well ecognized. Therefore, extensive investigations of liquid sloshing have been conducted and reported. However, the research data on the surface responses of a magnetic fluid ubject to magnetic fields and vibrations are insufficient, and there are many points which nust be clarified.

In this report, the dynamic behavior of magnetic liquids in cylindrical containers subject o magnetic fields and oscillatory fields was investigated theoretically and experimentally. The effects of magnetic field gradients on magnetic fluid sloshing were revealed.

2 Theory and Experiment

The wave motion theory developed in this report is valid only for low-frequency container vibrations for which the container may be assumed to behave as a rigid container, and surface tension and magnetic normal traction effects on the surface waves have been neglected. The aim of the theoretical analysis is to predict the effect of magnetic field gradients on the amplitudes of the liquid free surface motions and the frequency bands for which such motions are possible. The velocity potential theory was adapted to the problem of lateral and longitudinal sloshing in a circular cylindrical container. The numerical calculation revealed some effect of magnetic field gradients on the amplitudes of liquid surface motions and the unstable regions for several one-half subharmonic modes.

Experiments were performed on a vibration-testing system. A permanent magnet and an acrylic plastic container were mounted on the vibrating table of the electrodynamic shaker. The cylindrical container, 107mm long, 40mm inner diameter, 10mm thick, with a 10mm thick flat bottom and an open top, was used in this experiment. The container was filled with magnetic fluid, water-based ferricolloid W-35, to the specific level. The displacement of the magnetic fluid free surface was measured with the optical displacement detector system. The dynamic behavior of the magnetic fluid surface in the container was recorded by a 16mm high-speed camera.

3 Results and discussion

Magnetic liquid surface responses to lateral and longitudinal excitation exhibit a variety of characteristics, all of which depend principally upon the excitation amplitude, excitation frequency, and magnetic field gradient. The natural frequencies of magnetic liquid surface modes shifted to higher frequencies when the magnetic field gradient was negative, while they shifted to lower frequencies when the gradient was positive. Theoretical prediction of regions of one-half subharmonic instability by the Mathieu equation seems to agree very well with experimental data.

IMPACT BETWEEN A MAGNETIC LIQUID DROP AND A LIQUID SURFACE

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1 Introduction

The study of the impact between a liquid drop and a liquid surface is of fundamental interest and importance in science. Since a detailed investigation of the flow configuration produced by the impact of a liquid drop against a target liquid was carried out by A.M.Worthington, a number of investigations of liquid impacts have been conducted. However, the research data on the splashing of magnetic liquid drop on an usual liquid surface are insufficient, and there are many points which must be clarified. Further, the effect of applied magnetic field on the splashing of magnetic drop is not known.

In this report, the subsurface phenomena and the splashing for impacts of magnetic liquid drops against kerosene with or without the applied magnetic fields were investigated experimentally. The effect of various concentrations of magnetic fluids upon the subsurface phenomena and the difference in target liquids were discussed.

2 Experimental apparatus and procedure

Magnetic liquid drops were formed with a 50ml burette. The drops were made to fall through the beam of a laser and the hole of a drop cutter. The drops of magnetic fluid fell into the transparent rectangular tank which contained target liquid. The splashing of the drop was recorded using a high-speed movie camera operated at 2000 frames per second. The impact phenomena were filmed by sidelight illuminated from two 1kW lamps. This method enabled us to recognized two-fluids,that is, colored drop fluid and transparent target fluid. The subsurface phenomena and splashing were analyzed by a film motion analyzer. Sample liquids used in the experiments were water-based ferricolloid W-35 and its dilution with distilled water as drops, and kerosene or distilled water as target liquid. A permanent magnet was installed under the liquid tank, and the effect of magnetic fields on the subsurface phenomena was investigated.

3 Results and discussion

Without applied magnetic fields, the sequence of events following the impact of a magnetic drop was found to be similar to one of a water drop in the formation of subsurface cavity and the Rayleight jet. Following the impact, the interior of the cavity was lined by the magnetic fluid which formed the drop, but the magnetic fluid descended to the bottom during the growth of cavity. The part of magnetic fluid left the cavity with shrinking of the cavity, but the remaining one ascended with the rising of the liquid column. This column was the compound Rayleigh jet.

On the other hand, with applied magnetic fields, the sequence of events was very different from the above. The magnetic drop collided as if solid body collided with water. The drop did not disintegrate through the falling in kerosene for about 10ms after the impact. The cavity depth formed by impact was shallow extremely.

MAGNETORHEOLOGY IN STRONGLY STRUCTURED MEDIA

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When the magnetic energy due to the application of an external field is much larger than kT the suspension becomes strongly structured and we end up with a phase separation. The size of the domains which are formed can be deduced from a minimization of the magnetostatic energy. In this paper we shall present some theoretical and experimental results concerning the initial permeability of a suspension composed of silica particles in a ferrofluid; these results are obtained both for homogeneous and structured suspensions.The resistance of these structures to a deformation gives rise to a shear modulus and to a yield stress which can be measured and compared to the theoretical predictions based on some structural hypothesis concerning the motion of the aggregates submitted to a shear stress.We shall show that the shear modulus is a quantity which is much more sensitive to the structural aspect than the yield stress.The implications of these observations on magnetorheology as function of the size of the particles will be discussed.

Heat and Mass Transfer

CONCENTRATION GRATING IN A MAGNETIC FLUID

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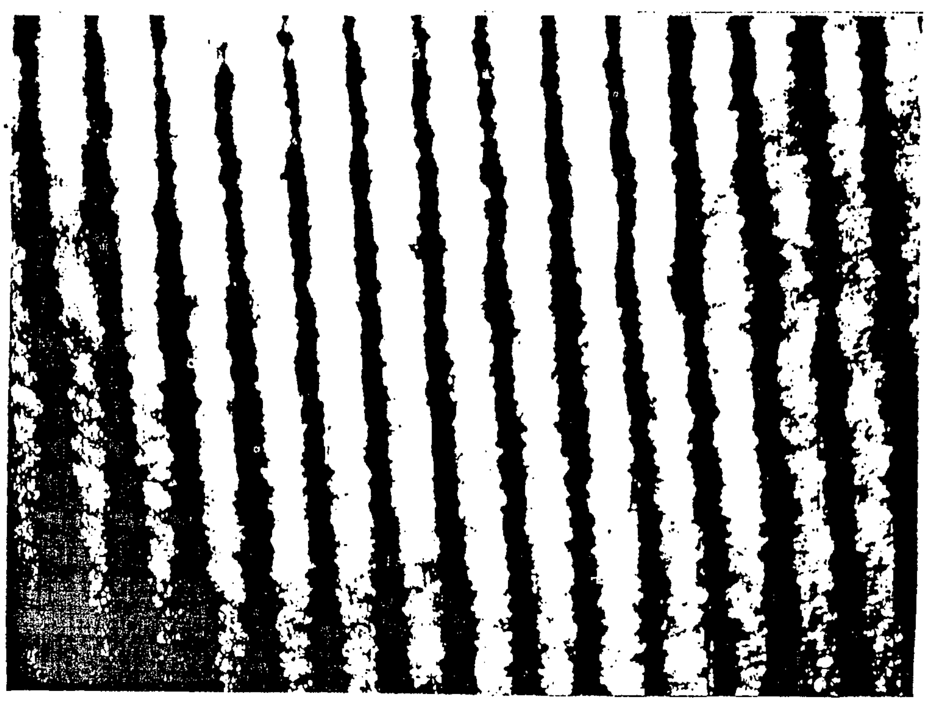
With an interference pattern, it is possible to write a grating of concentration in a Magnetic Fluid with a spatial period from 5 μm to 50 μm. The picture shows a concentration grating with a spatial period of 15 μm.

– Due to the electric field gradients of the interference pattern and to the induced electric dipoles, particles are submitted to periodical electric forces leading to an electrostrictive effect.

– Due to the light absorption by the magnetic fluid, a stationnary thermal grating is also induced. Depending on the sign of the thermodiffusive coefficient, this effect helps or not the building of the concentration grating.

Nethertheless the translational Brownian diffusion is a limiting factor for the concentration contrast. The dependence of the concentration contrast and of the characteristic rising time with the spatial wave vector is a way to analyse these different phenomena.



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CONVECTION IN THERMOMAGNETIC DIFFUSION COLUMN: UNSTEADY EFFECTS CAUSED BY PARTICLE TRANSFER IN FERROFLUIDS

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Recently a new phenomenon - a thermomagnetophoresis of colloidal particles in ferrofluids - theoretically has been predicted. Numerical estimates show that the thermodiffusion ratio for magnetic nanoparticles, especially when temperature- sensitive ferrofluids are considered, may reach the value typical for conventional thermodiffusion of molecules in liquids. The main task of the given paper is to clarify problems necessary to develop a theory available for nanoparticle thermodiffusion mobility measurements in ferrofluids by using a vertical thermodiffusion column.

Thermodiffusion columns are widely used in the modern radioisotope separation technology. Theory of separation in vertical columns has been developed by use a supposition that the free convection in liquid is caused only by thermal buoyancy force. When nanoparticle transfer in magnetic fluids is under consideration, such simplification is not valid. The density of the magnetic nanoparticle material is significantly higher than that of the carrier liquid. Therefore, even a small concentration nonhomogenities developed during the particle thermophoresis across the channel, causes a significant redistribution of buoyancy force. Thus, the theory of thermodiffusion column have to be modified considering the mixed convection effected by thermal as well by concentration buoyancy forces. The more simple theory is developed taking as a basis a quasistationary mass transfer in flat channel between two infinite plates when stationary particle distribution across channel is reached. It is shown in the paper that for stationary convection the integral mass transfer equation for the column may be written in a form of nonstationary diffusion equation. Both, the convective diffusion coefficient D^* and the convective vertical particle separation velocity u^* depend on thermal Gr_T and on concentration Gr_n Grashof numbers as well as on the Scmidt number of colloidal particle dispersion Sc. Effect of particle transfer on the convection velocity in column is very high. Due to low values of magnetodiffusion Fourier number Fo_D even in columns having extremely thin gaps d the convection is strongly unsteady. In order to evaluate the effect of convection nonstationarity on the kinetics of particle separation, a quasi- stationary one- dimensional convection in infinite vertical flat channel was analyzed. For small separation parameter $k = u_T d/D$ values (D is the particle Brownian diffusion coefficient, u_T is the particle thermodiffusion velocity across the channel) the following relation in the stationary regime is valid: $u^* = k(D/d)(Gr_T - kGr_n)Sc/6!$. In the presence of intensive thermophoresis if $k > Gr_T/Gr_n$, the particle vertical separation velocity is directed along the vector of gravitation acceleration independently of the sign of thermodiffusion coefficient. In a nonstationary regime the convective particle flux increases monotonously from zero (at $Fo_D = 0$) to the corresponding stationary flux value which is reached when $Fo_D > 0.2$. In columns oft the height $L >> d$ such time interval is considerably less than the relaxation time of mean particle concentration in upper and in lower chambers during the separation. Therefore, the kinetics of particle separation in thermodiffusion column may be considered in the approximation of stationary convection, except the short time interval $t < 0.2\ d^2/ D$ of the initial nonstationary regime.

ABOUT SOLID AND MAGNETIC PHASES IN MAGNETIC FLUIDS

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In allmost applications we need magnetic fluids (MF) with high saturation magnetization and low dynamic viscozity coefficient. For a given type of MF, the saturation magnetization is given by the volume concentration of the magnetic phase ε_M, whereas the dynamic viscozity coefficient is given by the volume concentration of the solid phase ε_S. A high quality MF must have a high value of the ratio $\gamma=\varepsilon_M/\varepsilon_S$, named the conversion parameter of magnetic properties.

A lot of authors have shown that ultracentrifugation and High Gradient Magnetic Separation (HGMS) are two different methods which allow the obtaining of MF with different values of ε_M, ε_S and γ. Different distribution functions of the particles on their volumes or magnetic moments are also obtained by these two methods. The paper presents our experimental results and discussions related to the possibilities to obtain MF with high parameter γ, as well as the physical significance of this parameter.

The mean reasons for which the volume concentrations of the magnetic and solid phases are different, are the following:

a) The presence of clusters, aggregates and non-monodomenic particles in the MF. These give a low contribution to the magnetic phase but a high contribution to the solid phase. The decreasing of clusters, aggregates and non-monodomenic particles number lead to a increase of parameter γ values.

b) The nonmagnetic layer from the particles surface, determined by the interactions from the interface particle-surfactant. The decreasing of the particles volume lead to a decreasing of the parameter γ values.

c) The effective magnetic moments of the particles. The decreasing of the effective magnetic moments of the particles, caused for example by the preparation method or by oxidation phenomena, lead to a decrease of the parameter γ values.

The mentioned reasons were experimentaly verified for MF based on magnetite particles coated with oleic acid and dispersed in kerosene.

The ultracentrifugation of MF at 10000 rot/min. and for a time of 15 min. allows the obtaining of final MF (except sediments) with a maximum value of parameter γ, because clusters, aggregates and non-monodomenic (large) particles are removed with the sediment.

The HGMS processing of the MF was made using a separation cell with ferromagnetic randomize wires. The ultracentrifugated MF with the maximum value of γ was passed through the separation cell, at low magnetic field intensity. The particles retained on the ferromagnetic wires were dispersed in the basic liquid. The MF which was passed through the cell was processed in the same way, but at increasing values of the magnetic field intensities applied to the cell. With the increasing of the external magnetic field intensity applied to the cell, particles with decreasing magnetic moments are retained on the wires. By the dispersion of these particles in the basic liquid, we have obtained final MF with different mean magnetic moments of the particles. A decrease of the parameter γ values with the decrease of the mean magnetic moments of the particles was determined.

INFLUENCE OF MAGNETIC FIELD ON THE BUBBLES SIZE IN THE BOILING MAGNETIC FLUIDS

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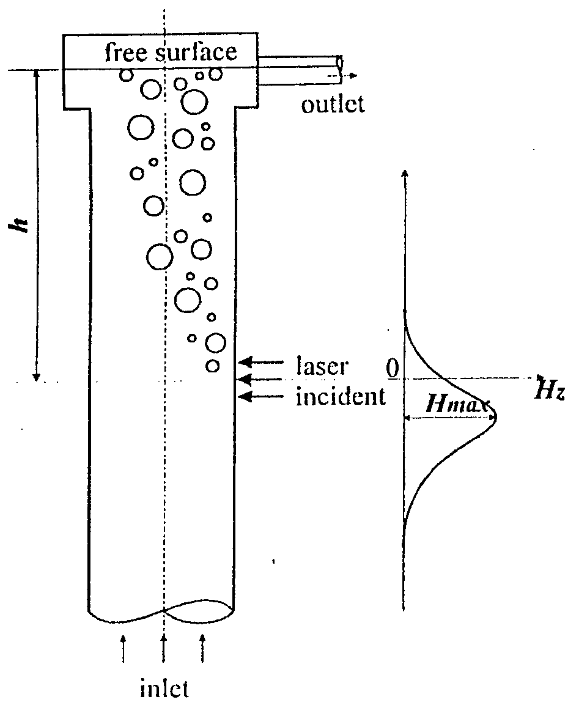

Recently the experimental results were presented [1] of study the magnetic fluid boiling by laser beam. The scheme of the experiment is shown on Fig. 1. It was discovered that size of the bubbles at the free surface of magnetic fluid depends on the magnetic field strength: Increasing of the strength leads to decreasing of the bubbles size. There are several factors influencing size of the bubbles in the boiling magnetic fluid in the magnetic field. First, size of the bubbles separating from the solid surface in the boiling fluid depends on the body force, it means on the gradient of magnetic field strength in the point of bubble formation: size of the separating bubbles decreases with increase in the body force. Second, the size depends on the difference of the pressure at the free surface and the pressure in the region of the bubbles formation, i.e. on the value of magnetic field strength: The greater magnetic field is, the greater bubbles size is. At last, pressure in the bubble depends on the temperature. There is a high temperature in the region of laser incident and fluid boiling, and a bubble gets cool during the way to the free surface, so, the pressure in the bubble and, hence, the bubble size decrease during this way. So, some factors act to decrease the bubbles size and some of them to increase the size.

The present paper deals with an attempt to estimate the contribution of this factors. In the gravity force field the size of bubble separating from the solid surface is defined by the equality of the buoyancy (Archimedean force) and the surface tension force:

$$\rho V g = \sigma L \tag{1}$$

where ρ is a fluid density, V is a bubble volume, L is a length of the contact line of bubble and solid surface and σ is surface tension. If the bubble in the moment of separating from the solid surface has a shape of a semisphere R_0 in radius then Eq.(1) has the form

$$\frac{2}{3}\pi R_0^3 \rho g = \sigma 2\pi R_0 \tag{2}$$

and we have well-known condition of separating a bubble from the solid surface in boiling fluid

$$R_0 = \sqrt{3\sigma / \rho g} \tag{3}$$

As radius of a free spherical bubble R_h and radius of semispherical bubble at a solid surface are connected as $R_0 = \sqrt[3]{2}\, R_h$ (it follows from the condition of their volume equality), the first one is equal

$$R_h = \frac{1}{\sqrt[3]{2}} \sqrt{\frac{3\sigma}{\rho g}} \tag{4}$$

A pressure in the fluid P_h is

$$P_h = \rho g h + P_0 \tag{5}$$

where P_0 is a pressure at the free surface, h is a depth of the point of bubble formation. The relationship

$$\frac{P_h V_h}{T_h} = \frac{P_0 V_0}{T_0} \tag{6}$$

must be fulfilled (V is a volume, T is a temperature, indexes "h" and "0" correspond to the depth h and to the free surface, respectively). It means the volume of a bubble at the free surface is

$$_0 = V_h \frac{P_h T_0}{P_0 T_h} = V_h \frac{(P_0 + \rho g h)\, T_0}{P_0 T_h}$$

A bubble at the free surface has a shape of a semisphere, so, its radius R_S is

$$R_S = \sqrt{\frac{3\sigma}{\rho g}} \sqrt[3]{\frac{(P_0 + \rho g h)\, T_0}{P_0 T_h}} \tag{7}$$

We will use an analogy of the gravity and magnetic body force. In this case instead of gravity force density ρg we must use magnetic body force density $\mu_0 MG$, where M is magnetic fluid magnetization and G is magnetic field strength gradient. Magnetostatic pressure in magnetic fluid is $\mu_0 MH$ and radius of the bubble at the free surface of magnetic fluid under the magnetic field is

$$R_S^H = \sqrt{\frac{3\sigma}{(\rho g + \mu_0 MG)}} \sqrt[3]{\frac{(P_0 + \rho g h + \mu_0 MH) T_0}{P_0 T_h}} \tag{8}$$

In this case the influence of magnetic field on bubble size at the free surface of magnetic fluid is given by the ratio

$$\frac{R_S^H}{R_S} = \sqrt{\frac{\rho g}{(\rho g + \mu_0 MG)}} \sqrt[3]{\frac{P_0 + \rho g h + \mu_0 MH}{P_0 + \rho g h}} \sqrt[3]{\frac{T_0}{T_h}} \tag{9}$$

One can see from Eq.(9) that radius of the bubble at the free surface of magnetic fluid decreases with the increase of the gradient of magnetic field strength and the temperature of boiling fluid. The bubble radius increases with the magnetic field strength. In order to estimate the complex effect of all three factors we will use experimental data [1]. The magnetic fluid used in the experiment has the following physical properties: density ρ = 1386 kg/m^3 (T = 283 K), surface tension σ = 0.0213 N/m (T = 283 K). The magnetization M is expressed as a function of temperature T and magnetic field H as

$$M = 3.108 \cdot 10^{-5} f(H) g(T)$$

where

$$f(H) = 290 + 0.171 H_z - 6.809 \cdot 10^{-7} H_z^2 + 1.007 \cdot 10^{-12} H_z^3 \quad (H_z < 115.3 \text{ kA/m})$$
$$g(T) = 6.675 \cdot 10^4 - 130.07 T.$$

There were two values of maximum magnetic field strength ($H_{max}^{(1)}$ = 57.7 kA/m and $H_{max}^{(2)}$ = 115.3 kA/m) in the experiment. They correspond to the following values of magnetic field strength H and gradient of magnetic field strength G in the point of laser incident: $H^{(1)}$ = 39.9 kA/m, $H^{(2)}$ = 73.8 kA/m, $G^{(1)} = 0.97 \cdot 10^6$ A/m^2, $G^{(2)} = 0.97 \cdot 10^6$ A/m^2. For the first value of magnetic field the temperature of boiling magnetic fluid was $_h^{(1)}$ = 334 K and for $H_{max}^{(2)}$, $_h^{(2)}$ = 324 K. Depth of the laser incident point was h = 0.67 m. For these two values of magnetic field we can calculate from Eq.(9) the change of bubble radius

$$\frac{R_S^{H^{(1)}}}{R_S} = 0.85 \times 1.009 \times 0.957 = 0.82 \tag{10}$$

and

$$\frac{R_S^{H^{(2)}}}{R_S} = 0.67 \times 1.02 \times 0.967 = 0.66 \tag{11}$$

From the equalities (10) and (11) one can see that the main factor influencing the bubbles size is a gradient of magnetic field strength. On the other hand, the effect of temperature and magnetic field strength is very weak. Experimental data [1] gives values of bubbles radii ratio

$$\frac{R_S^{H^{(1)}}}{R_S} = 0.51, \qquad \frac{R_S^{H^{(2)}}}{R_S} = 0.14 \tag{12}$$

Comparison of experimental data (12) and theoretical estimations (10) and (11) shows essential quantitative difference. Probably, the main reason for such difference is our supposition of semispherical shape of a bubble at solid surface in the moment of separating from the surface. Real shape of the bubble in boiling magnetic fluid depends on the value and direction of magnetic field and Eq.(2) does not follows from Eq.(1). In the absence of magnetic field supposition of

semispherical bubble shape is rather good: In accordance with Eq.(7) radius R_S is equal to 2.1 mm and the experimental data is R_S = 1.75 mm. The reason of slightly different theoretical and experimental values could be nonequality of the wetting angle to 90°: In this case shape of a bubble is not semisphere. Magnetic field change shape of bubble and shape of its contact line with solid surface and decreases bubble size much more, then it follows from theoretical estimations based on the supposition of semispherical bubble shape on solid surface. The importance of taking into account such factors as shape of a drop and wetting angle at the solid surface follows from the results of the study of inverted situation: Separation of magnetic fluid drop from solid surface [2-4]. Both theoretical [2] and experimental [3,4] data show that volume (so, radius too) of separating magnetic fluid drop decreases with increasing of wetting angle and magnetic field. The same situation could be in the case of separating bubble in magnetic fluid.

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NONSTATIONARY FERROFLUID PARTICLES SEPARATION IN THERMODIFFUSION COLUMN

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Transport properties of magnetic nanoparticles play a significant rule in the problem of long- term stability of magnetic fluids. Usually, in research the attention has paid only to the gravitation sedimentation and to the magnetophoretic separation of ferroparticles. Nevertheless, in many magnetofluid devices, for example, in high speed rotary seals or in loudspeaker cooling systems when high temperature gradients are present, the long- term stability of magnetic fluid may be effected also by a thermophoretic nanoparticle transfer. It is well known that thermophoretic velocity of particles in aerosols and in gaseous dispersions may reach a value significantly higher than that in molecular gases and liquids. Some experiments, for example, these of particle grating in optical interference bands (the forced Rayleigh scattering experiment), indirectly indicate a high thermophoretic mobility of particles in colloidal dispersions also. In the present paper some results of macroscopic experiments on particle thermodiffusion in ferrocolloids are presented.

Experiments are performed by using a vertical thermodiffusion column. It includes a flat channel formed by heated and cooled side walls and upper and lower separation chambers. Due to the free convection and the thermodiffusive particle transfer across the channel a particle concentration difference in both chambers Δn develops. According to the column theory the particle separation rate $d(\Delta n)/dt$ in initial stage of separation is constant. If volumes of upper V_u and lower V_l containers are equal, $V_u = V_l = V$, from theory follows a relation $\Delta n = 2u^* t S/V$ with S being the cross section of the vertical column of width d and u^* - the generalized particle separation rate which includes both the gravitation sedimentation velocity u_g and the thermodiffusive convective particle transfer velocity u_c. The later, according to the column theory modified for colloids in which the particle separation is determined by mixed (thermal and concentration) convection, depend on thermal Gr_T as well as on concentration Gr_n Grashof numbers: $u_c = (D/d)k(Gr_T - kGr_n)Sc/6!$. Here D is the particle Brownian diffusion coefficient, Sc is the Schmidt number and k is the nondimensional thermodiffusion parameter which is proportional to the thermodiffusion ratio α_T: $k = \alpha_T \Delta T/T$ (T is the temperature difference between column walls).

Experiments were performed by use a column of height $L = 7.5$ cm and width $d = 0.5$ mm, its volume is equal to the volume of upper and lower containers. Particle concentration during the separation experiment was determined by an inductive method using resonance frequency measurements. Induction coils are mounted in inside the separation chambers. Tetradecane based ferrofluids containing magnetite particles were used in the experiments. The saturation magnetization of fluid $M_s = 15.2$ G/g, the mean particle diameter determined by magnetogranulometry analysis $2a = 7.7$ nm. For $\Delta T \approx 2$ C a concentration difference $\Delta n > 0.5 n_0$ in the stationary regime of particle separation was obtained. Such separation rate correspond to the values of α_T approximately equal to 50. Thermodiffusion coefficient measurements are discussed in the paper.

CONVECTION DRIVEN BY FORCED DIFFUSION IN FERROFLUIDS

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Due to their colloidal makeup and their long term stability, which allows reproduction of experiments, ferrofluids are excellent model substances for many problems. This is, for example, valid for the high gradient magnetic separation (HGMS) of magnetically marked particles from carrier liquids. This process, used e.g. for many medical problems like separation of blood cells or extraction of lymphozytes, has been in the interest of a large number of theoretical and practical investigations. Part of the work was focussed on the final state of the demixing process of a suspension of magnetic particles in a carrier liquid subjected to a strong magnetic field gradient. Another part of the investigations dealed with a special effect taking place during the beginning of the demixing process. Shortly after appliing the magnetic field gradient to the suspension a gradient in concentration of the magnetic component antiparallel to the magnetic field gradient develops. The interaction between the gradient in magnetization in the suspension, which is given by the concentration gradient, and the field gradient itself gives rise to a convective flow. This nonequilibrium process is of great importance for the demixing process since it amplifies the velocity of demixing over the normal diffusion velocity. Nevertheless only indirect experimental verification of the phenomenon had been given for many years due to measurement problems.

In our experiments we have choosen a cylindrical geometry consisting of magnetic fluid enclosed by two concentric cylinders under the influence of an azimuthal magnetic field produced by a current leading wire in the cylinder axis. The azimuthal field provides a radial gradient forcing the demixing process. This geometry was choosen in comparison to theoretical investigations carried out by Chukhrov.

In a number of experiments carried out in such a cylindrical geometry we have measured on the one hand the evolution of the radial concentration distribution between the concentric cylinders as a function of time. On the other hand we have investigated the onset of convection by measuring the flow velocity by means of thermal anemometer.

The results of the concentration measurements carried out with an inductive method are compared with numerical solutions of the diffusion equation appropriate for the problem. In particular the increase of concentration antiparallel to the magnetic field gradient has been found. The velocity measurements showed a convective motion. The data obtained for the velocity is compared with a model basing on time dependent dimensionless parameter. In addition it could be found from the data that the velocity of the demixing process exceeds the normal diffusion velocity. This result is a strong indication for the prediction of Blums that showed an amplification of the diffusion velocity by the convective motion.

Physico-Chemical Aspects and Physical Properties

PREPARATION AND PROPERTIES OF Mn-Zn FERRITE PARTICLES FOR IONIC FERROFLUID SYNTHESIS

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Particular ferrofluids constituted by mixed ferrite,containing Zn may be good candidates for liquid carriers in heat-exchange devices using magnetocaloric energy convertion due to these specific physical properties: low Curie temperatures and high thermomagnetic coefficients (1).

Fine particles of mixed Mn-Zn ferrites were synthesised with different initial ratio Mn/Zn, using Massart's chemical procedure. The first step of this synthesis implies coprecipitation of the mixture of metal salts with a base and aging of obtained particles at boiling conditions. This first step is largely responsible for size and magnetic properties of particles in final ferrofluid.

Influence of the nature of the alkaline medium used for coprecipitation.

Three different alkaline media have been used as agents for coprecipitation. It was shown that these media give particles with size diminishing in following sequence: $NaOH > CH_3NH_2 > NH_3$. Moreover, each base hase is its own zone of optimal ratio Mn/Zn, for which reactions of coprecipitation and ferrite formation take place. For NH_3 and CH_3NH_2, when content of Zn exeeds certain amount, formation of nonmagnetic roentgenoamorthous product is observed. The other interesting feature is that an increase of initial molar ratio Mn/Zn (within the zones mentioned above) leads to formation of particles of bigger size. For example, in the case of methylamin (CH_3NH_2) we have obtained the following evolution of size:

initial molar ratio Mn/Zn/Fe	Drx, Å
0.5/0.5/2.0	60
0.8/0.2/2.0	68
1.0/0.0/2.0	99

where Drx is mean diameter of particles after first step of synthesis, obtained from the analysis of the X-rays peak enlargement

Thermomagnetic measurements.

Magnetization curves were performed at different temperatures (20°, 50°, 100° and 150°C) on dried samples , both for particles after first step of synthesis and final particles (dried ferrofluids). Thermomagnetic curves were built up as a function of maximal specific magnetization values (in magnetic field of 20 kOe) on temperature. Almoust all samples demonstrate approximetly linear thermomagnetic behaviour in the temperature range 20-100°C. Thermomagnetic coefficients were determined as slopes of thermomagnetic curves in the temperature range 20-100°C. The ratio Mn/Zn in particles has a noticeable influence on the absolute values of their specific magnetization. It seems that the greater is the ratio Mn/Zn, the higher is the specific magnetization. It may be partly related also to the increase of the mean size of particles mentioned above. Thermomagnetic coefficients present small variations (0.19 - 0.23 $G \cdot cm^3/g \cdot K$) at least in the range of initial molar ratios Mn/Zn/Fe: 0.5/0.5/2.0 - 0.8/0.2/2.0.

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MEDIA PROBING WITH MAGNETIC PARTICLES

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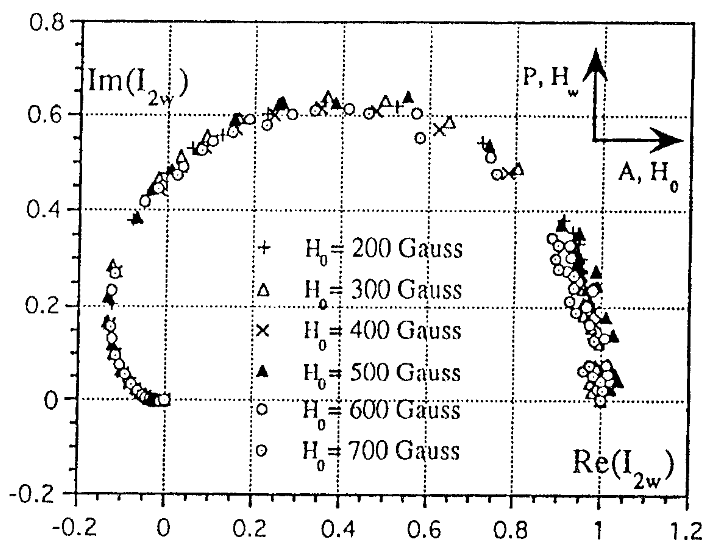
The goal of this work is to propose a new method to study the intrinsic structure and kinetics processes of complex fluids (organic/inorganic gels, polymer solutions, liquid crystals or melts). Rheological properties of these media are not scale-invariant : the results of measurements are dependent upon the relation between the size D of the mechanical probe and the intrinsic scale (or scales) d of a fluid. Conventional rheometers, though offering numerous opportunities of testing regimes, always remain in the $D \gg d$ range. To achieve the scale $D \sim d$ or $d < D$, and thus get into direct touch with the intimate details of the fluid structure without destroying it, the probe itself must be of a nanoscale size. Ferrite particles of diameter $D \leq 10$ nm fit the demand very well. These magnetic particles are suspended in the fluid under investigation in tiny amounts ($\leq 10^{-3}$ vol.%). Crossed magnetic fields are applied on the sample : a static one, H_0, and a sinusoidal one of lower amplitude, H_w. Analysis of the magneto-optical response of such a suspension provides an efficient insight of its internal structure and rates of kinetic processes. From these measurements one is able to determine viscoelastic properties of suspending medium.

In zero external field the sample is optically isotropic. Under fields the particles orientate leading to an uniaxial optical anisotropy of the medium which becomes birefringent. Induced birefringence is studied in the frequency range 1 Hz to 10 kHz, recording the first harmonic I_{2w} of the laser beam transmitted by the sample put between crossed polarizer (P) and analyzer (A) (see inset in the figure).



Cole-Cole plot of the measurements; maghemite particles; $H_w = H_0/10$

VORTICO-MAGNETIC RESONANCE

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A magnetization measurement is proposed to investigate the coupled response of a ferrofluid to an external time dependent magnetic field and to a vorticity of the carrier liquid. In the rigid dipole approximation, magnetic particles, submitted to an external magnetic field, align their magnetic moment by rotating their body itself. In the experiment, the instantaneous orientation of the particles results from competition between hydrodynamic dissipative energy and magnetic energy.

Switching off the magnetic field, a transient regime of the magnetization is observed with a characteristic time equal to the Brownian rotary diffusion time $\tau_B = \frac{3\eta V}{kT}$. If the carrier liquid has a vorticity Ω perpendicular to the magnetic field, the decrease of the transverse magnetization M_t is modulated at the same frequency as the vorticity of the flow *(figure 1)*. As a general rule, the magnetization evolution is driven by the phenomenological equation :

$$\frac{d\vec{M}}{dt} = \vec{\Omega} \times \vec{M} - \frac{\left(\vec{M} - \chi_0 \vec{H}\right)}{\tau_B}$$

From the analogy of this relation with Bloch equation (the vorticity playing the role of the Larmor precession frequency), a resonance phenomenon is expected, using an oscillatory magnetic field H of frequency ω, if $\omega^2\tau^2 = 1 + \Omega^2\tau^2$ *(Figure 2)*.

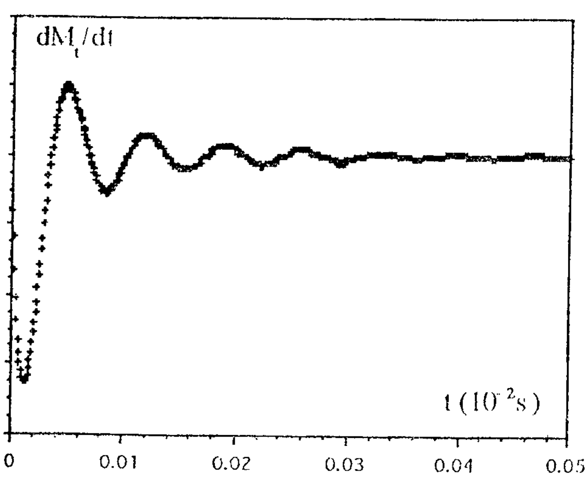

Figure 1

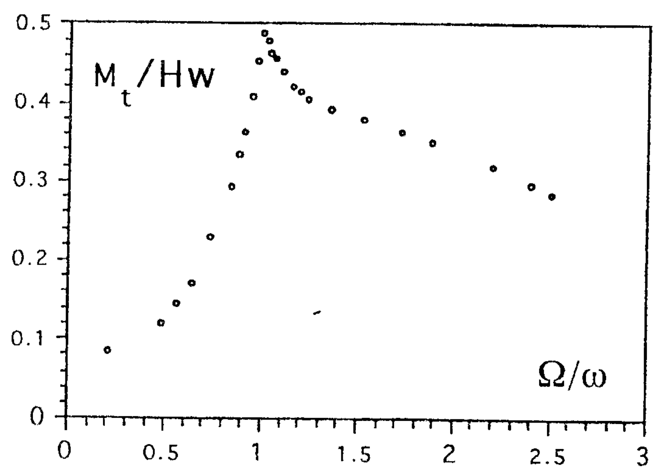

Figure 2

This experiment may be developped for a local vorticity measurement using NMR imagery in a medium doped with magnetic particles.

PHASE TRANSITION IN STRUCTURIZED MAGNETIC FLUIDS

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The magnetic properties of magnetic fluids (MF) of high viscosity (of about 0,4 to 10 Pa c) were investigated. These MF are prepared on the basis of siliconorganic combinations and have well developed structural net formed by dispersed particles.

These magnetic fluids of grate practical importance. The measurements of MF magnetization were carried aut by the ballistic method (with error smollen then 2%), and the study of real (x') and imaginary (x'') part of the complex magnetic susceptibility - by the bridge method, and by using the measured parameters of solenoid being filled up by MF spesimen.

In the recent works [1,2], we have established that the magnetizatin curves have have a histeretic nature and the temperature dependence of the susceptibility real part has maximum in the temperature region, corresponding to liquid state of MF. As it has turned the magnetude of residual magnetization depends on the magnetizing temperature and intensity of magnetizing field (Fig.1). This means that the peculiarity of magnetization depend on the investigated structure. This assumption can be confirmed by the investigation results of the susceptibility real and imaginary part dependens on the magnetic field intensity (Fig. 2, curves 1,2 and 3 correspond to field frequencies 110 Hz, 340 Hz and 7 kHz, accordingly). As it seen the x'(H) and x''(H) have maxima at any values of magnetic field intensity, that does not depend on the measuring field frequency. This Fig.1 fact means that maxima depende on the structure of MF.

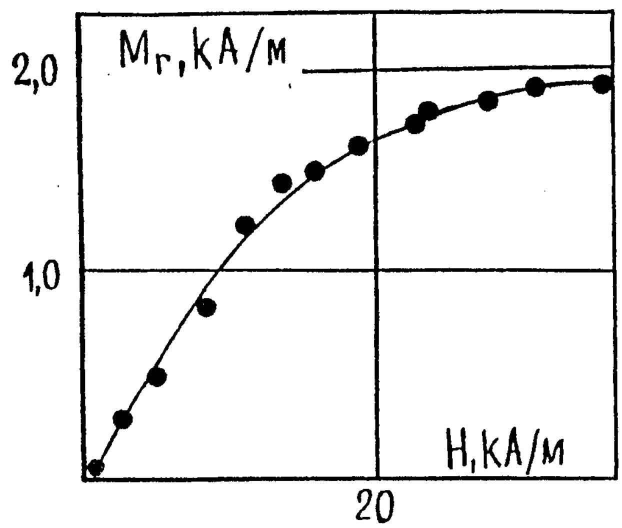

Fig.1

The presence of strustural formation have an influence on the frequency dependence of complex magnetic susceptibility real part. As it is seen from fig.3 x' decreeses submit to logarithmic low when magnetic field frequency increeses (1 -H = 0, 2 - H = 1,2 kA/m, 3 - H = 2,4 kA/m, 4 - H = 3,2 kA/m)

The structure formation leads to decrees of the distance between the dipole fraction, that leads in its turn during the MF magnetization to the increes of dipole minteraction role. As a result in MF agregates can take place a magnetic phase transition. This akility was shown in the recent work [3], were the magnetization peculiarity of MF on the basis of kerosine at the temperatures near its freezing-poind were carried aut. Then al-

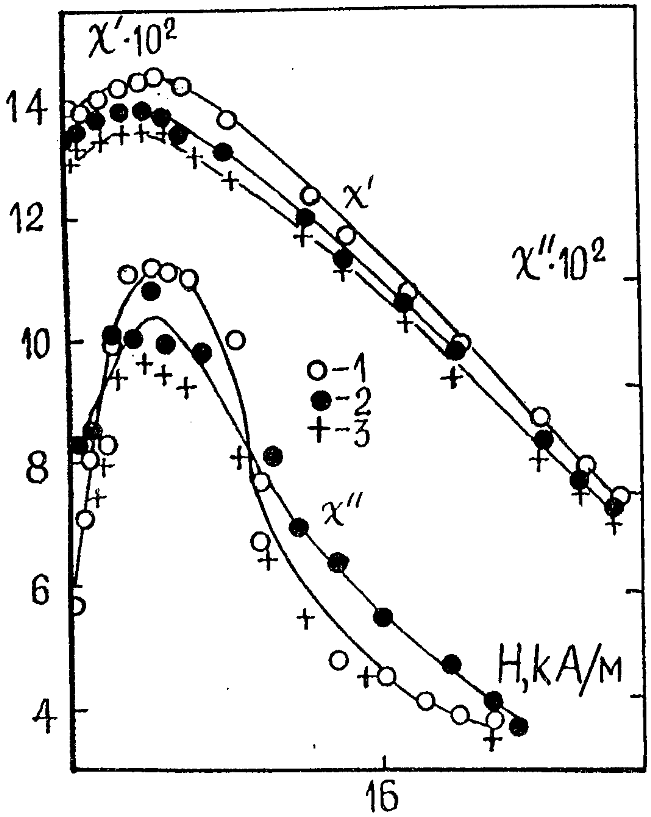

Fig.2

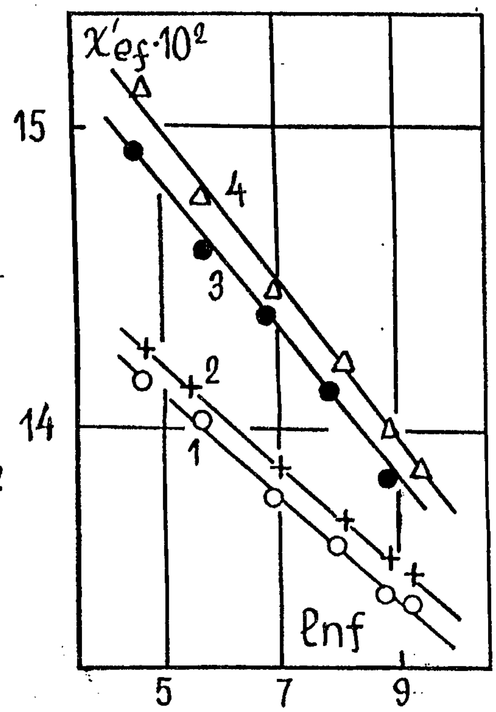

Fig.3

sow we made an assuption about the phase transition from superparamagnetic state to dipole glass, analogous to spin glass.For investigated now MF such conclusion can be made on the basis of analisis the recent and present results.

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NONLINEAR SUSCEPTABILITY AND VISCOSITY OF FERROCOLLOIDS NEAR THE HARDENING INTERVAL

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Many known anomalies of magnetic properties of ferocolloids are found near the hardening region of the carrier liquids [1].

The magnetization of magnetic material in ac magnetic field $h \exp(-i\,\omega t)$ is

$$M = \chi_0 h \exp(-i\,\omega t) + \chi_2 h^3 \exp(-3i\omega t),$$

were χ_0 is the linear susceptibility and χ_2 is the nonlinear susceptibility of the material.

The nonlinear susceptibility is more responsive to dimensions of magnetic particles and hence investigation of nonlinear effects in magnetization of ferrofluids provides a way of estimating the structure and the character of interaction of the colloidal particles. In this paper the temperature dependences of ac nonlinear susceptibility and viscosity of ferrocolloids were studied. The dynamic magnetic susceptibility was measured by the induction method. It is possible to measure the nonlinear susceptibility by measuring the magnetization on the third harmonic of the exciting field. The sample was excited by the field on the main frequency, the signal of the third harmonic was proportional to $\chi_2 h^2$ and was selected by selective nanovoltmeter. The systematic error from the presence of the third harmonic in the exciting field was taken into account by the corresponding correction. The viscosity of ferrofluids was measured by the capillary viscosimeter with the plane canal of the rectangular section. The temperature dependence of the nonlinear susceptibility $\chi_2 h^2$ and viscosity η kerosene-based ferrocolloid is shown in fig. 1. Sample was obtained by the repeated peptization and did not contain free oleic acid and another nonmagnetic impurities, the frequency of ac field 1.7 Hz, h_{ef} =2.2 Oe the concentration of magnetite $\varphi = 0.08$.

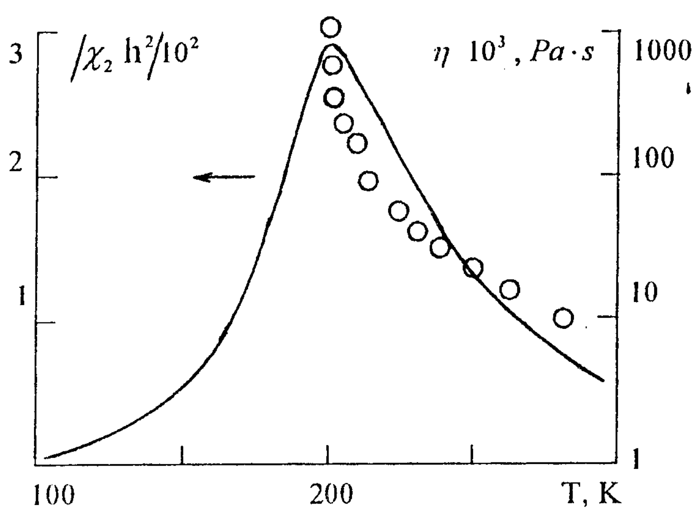

fig. 1

The temperature of susceptibility maximum T_* is near the 200 K for these samples. The sharp increase in the viscosity and the hardening of liquid was also observed in this region. This fact testifies that the rheological properties of the base

liquid are essential in the formation of the χ_2 $h^2(T)$ maximum. The same conclusion may be inferred from consideration of fig. 2, which represents the temperature dependences of linear and nonlinear susceptibilities of nonpurified colloidal solution of magnetite in octane with the concentration of the magnetite φ =0.23 and the melting point 216.4 K.

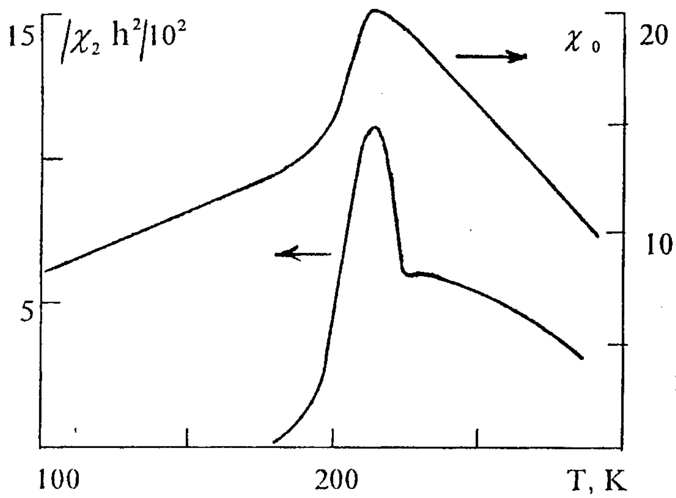

fig. 2

The linear susceptibility peak was observed at the melting point exactly. There was also a week maximum on the curve of linear susceptibility just bellow the T_*. The nonlinear susceptibility behaves in the same way as the linear one, however in this case the low-temperature peak was of greater intensity. The nature of this maxima is not clear. The autors of Ref. [2] belive that the reason for the additional maximum is the cooperative transition of the ferrofluid to the dipolar glass state. Such an interpretation seems to us to be unsatisfactory because the additional maximum disappears after purifying the ferrocolloid to remove the surplus of oleic acid and nonmagnetic impurities [1]. Notice that in the case of nonlinear susceptibility such sample purification had ever more influence: the low-temperature peak was absent and there was a maximum of χ_2 h^2 value at the melting point.

These peculiarities of the low-temperature behaviour of the susceptibilities contradict the spin-glass transition hypothesis, but are in good agreement with the model of the blocking of the rotational degrees of freedom of particles with the increasing viscosity of the carrier liquids.

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PECULIARITIES OF THE STRUCTURE OF MAGNETOFLUID LUBRICANTS

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The use of magnetic fluids (MF) as lubricating material in various tribotechnical devices (rotating and sliding bearings, gears etc.) provides to raise the reliability and life of machines and equipments. Tribological characteristics of these lubricants depend strongly on their physico-chemical structure. So the change of their physico-chemical structure variously influences on the different tribological parameters. For example the decrease of colloid stability of magnetofluid lubricants (ML) is the main cause of the increase of frictional surface; at the same time the frictional coefficient may be unchanged.

When saturated monomolecular layers of surfactant cover the the surfaces of particles there are two major reasons which decrease the colloid stability of MF in hydrocarbon oils. Firstly the presence of large magnetic particles leads to the formation of agglomerate magnetic drops without magnetic field. The removal of such particles by magnetic separation or centrifugation eliminates the reason of the decrease of colloid stability of MF. Secondly incomplete lyophilization of stabilized magnetic particles leads to the formation of the friable aggregative structure. The decrease of colloid stability is intensified with the increase of medium viscosity. Consequently there are supplementary measures for stabilization of MF in viscous (for example, vacuum) oils.

The presence of various additives (antifriction, antiwear, antifloat etc.) is the main difference between ML and MF. So the influence of various technological additives on the physico-chemical structure of ML is very different. Some additives such as copper oleat do not influence really upon the colloid stability of ML. Most of the additives interact with hydrocarbon radicals of surfactant molecules adsorbed on the surface of magnetic particles. The presence of some effective antiwear additives such as zinc ialkilditiophosphate decreases of colloid stability of ML causing the increase of frictional surface wear. The dispersity of the majority of additives hardly influence on the structure of ML too. When the colloid graphite is used its adsorption on the magnetic particles is the factor of some increasing of colloid stability of lubricants. The increase of graphite particles size up to O.2 micron is the result of the formation of aggregative structure.

When magnetic particles are stabilized by complex surfactant containing molecules of different length the greatest colloid stability of ML occurs. Such structure of stabilized magnetic particles increases the value of disjoining pressure between particles and increases their colloid stability in the presence of technological additives. The presence of a small quantity (less than O.1%) of some cationic surfactants increases the lyophility of stabilized magnetic particles and the colloid stability of ML too.

2D CONCENTRATION DOMAIN PATTERNS IN MAGNETIC COLLOIDS: ENERGETICAL AND KINETIC APPROACH

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Competing interactions determine the patterns arising at magnetic condensation in flat layers under the :tion of normal field [1],[2],[3]. Scaling of the structure period, magnetic overcooling with layer iickness are known from the linear theory [2],[3] and are in reasonable agreement with existing xperimental data [4],[5]. At present moment far from complete is understanding of the morphology of ie 2D patterns arising under strong magnetic quenches. Although mostly hexagonal patterns of the roplets of concentrated phase are observed [4],[5],[6] labyrinthine patterns are also possible. Here the ;sue concerning the type of the structure arising at magnetic condensation is considered from the different oints of view. In the first part energetical approach developed earlier [7] based on the calculations of the nergy of the periodical hexagonal and stripe patterns are carried out. The energy and equilibrium period f the hexagonal lattice of the microdrops of the concentrated phase with radius R_0 and volume fraction) in plane layer with thickness h determined from the relation

$$E = 2\pi\sigma S\left[\begin{array}{l} Bm\varphi(1-\varphi) + Bm\varphi\dfrac{4y}{3\pi x}\left(1-\dfrac{(2k^2-1)E}{k^3}-\dfrac{(1-k^2)K}{k^3}\right)+ \\ +\dfrac{M^2N}{2\pi\sigma S}\sum_{n\neq 0}\int dS\int dS'\left(1\Big/\sqrt{(\bar\rho-\bar\rho'+\bar\rho_n)^2}-1\Big/\sqrt{(\bar\rho-\bar\rho'+\bar\rho_n)^2+h^2}\right)\end{array}\right] \quad (1)$$

re calculated according to Evalds summation technique and "golden mean" method. Here σ - surface ension of the concentrated phase, N - number of domains per surface area S, $Bm = M^2h/\sigma$ - magnetic ond number, $k^2 = (2R_0/h)^2/(1+(2R_0/h)^2)$, E,K - elliptical integrals of the I and II kind, but $y = 2R_0/h, x = h/a$, where a - period of the structure. Energy and equilibrium period of the stripe attern l are calculated according to the relation [7], where $x = 2\pi h/l$

$$E = 2\pi\sigma S\left[\frac{h}{\pi l}-\frac{Bmh}{\pi l}\int_0^1(1-t)\ln\left(1+\frac{\sin^2(\pi\varphi)}{sh^2(xt/2)}\right)dt + Bm\varphi(1-\varphi)\right] \quad (2)$$

Numerical calculations according to the relations (1) and (2) of the energies of hexagonal and stripe hases show that at low volume fractions the hexagonal structure is energetically preferable. At large olume fractions about 50% the formation of the stripe phase is energetically advantageous.

Situations near the critical point can be described on the basis of the thermodynamical potential derived n [2],[3]:

$$\tilde F = h\int dS\left(-\frac{1}{2}\alpha(\delta n)^2+\frac{1}{4}\gamma(\delta n)^4+\frac{1}{2}\beta(\nabla\delta n)^2\right)+$$
$$+\left(\frac{\partial M}{\partial n}\right)^2\int dS\delta n(\bar\rho)\int dS'\delta n(\bar\rho')\left(1\Big/\sqrt{(\bar\rho-\bar\rho')^2}-1\Big/\sqrt{(\bar\rho-\bar\rho')^2+h^2}\right)$$

ntroducing the scalings following differential equation for the undimensionalized concentration n can be btained

$$\frac{\partial n}{\partial t}+\Delta\left(n-n^3+\Delta n-\frac{2Bm}{(h/l)^2}\int dS'n(\bar\rho')\left(1/|\bar\rho-\bar\rho'|-1\Big/\sqrt{(\bar\rho-\bar\rho')^2+(h/l)^2}\right)\right) \quad (3)$$

Numerical simulation of the magnetic field induced phase separation described by (3) was accomplished n the basis of the pseudospectral technique. For symmetrical distribution between concentrated and liluted phases according to the results of energetical calculations stripe phase in computer runs is bserved. Simulation from initial conditions corresponding to nonsymmetric distribution between :oncentrated and diluted phases show the structure with separated droplets or bubbles.

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MAGNETIC PROPERTIES OF MAGNETIC EMULSIONS

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Stady of micro-drop aggregates - widely spread structural form in the magnetic fluids (MF) - had been undertaken by a number of researchers and some of them identify MF with well developed micro-drop structure as magnetic emulsions [1].Of specific interest are also true magnetic emulsions obtained by emulsification of magnetic fluids in the media which does not mix with them.The former, like magnetic fluids with micro-drop structure, are used for visualization of magnetic heads' fields, for magnetic recording and in flaw defection.

In this work magnetic emulsions as a sistem of micro-drops of the maximum diameter 2-4 μm vere studied. To obtain such emulsions, methods similar to standard methods of preparation of oil-in-water type emulsions were used [2].

Magnetic susceptibility was studied by the bridge method with the help of the device which is described in detail in [3] and the range of error did not exceed 1%.In order to measure magnetization the method of ballistics was used, the error not exceeding 2%.

Under the influence of the magnetic field,magnetic fluid drops become magnetized, thus each of them acquires magnetic moment, the value of which is determined by the intensity of the magnetic field:

$$m = MV = \frac{xH}{1+xN_o} V$$

where x is susceptibility of the emulsified fluid,
N_o is drop demagnetization factor,
V is it's volume.

Complete energy of the magnetic emulsion includes energy of drop in the magnetic field, energy of their interaction and total energy of the interphase tension. Analysis of the expression for complete energy allows to obtain information on stable chain linked aggregates, which are formed in the magnetic emulsion under the influence of the magnetic field, but polydispersion of the actual emulsions makes rather difficult.

In this connection, the proccess of aggregates' formation was studied experimentally by microscopic observations and study of anisotropic light diffusion in thin layers of emulsion (30 to 40 μm) positioned in the magnetic field.Fig.1 shows dependence of the relative intensity of the anisotropic light diffusion on the field intensity at the diffusion angle equal to 5°. Analysis of this dependens makes it possible to assume, that the proccess of structures formation in the emulsion is actually completed at the values of field intensity 10 - 15 Oe. The proccess of structures' formation includes inflection of the magnetic emulsion magnetization and maximum dependence of the diffrential magnetic susceptibility on the field intensity (Fig.2, curves 1, 2 and 3 correspond to temperatures 20, 60 and 70° C,accordingly). Confirmation of that can be a sum of magnetization of the individual drops and those linked in chains.Thus, the following expression follows:

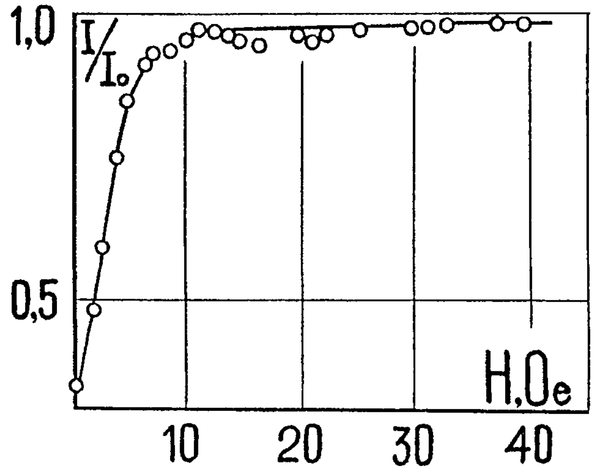

Fig.1

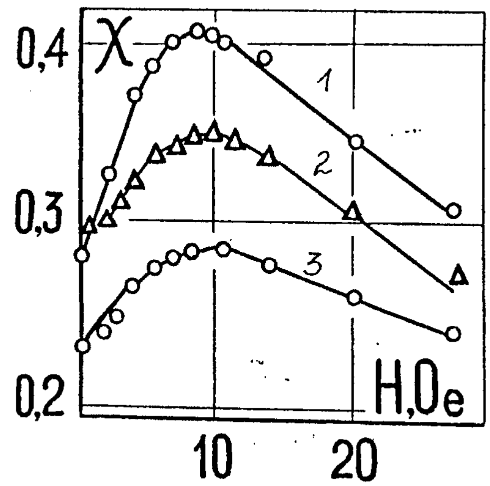

Fig.2

$$M = \frac{\theta x H}{1+xN_o} + \frac{\theta_1 x(N_o - N)H}{(1+xN)(1+xN_o)} \qquad (1)$$

where θ is volume concentration of all drops,
θ_1 is volume cjncentration of drops linked into chains,
N - demagnetization factor of the chain aggregate,
N_o - demagnetization factor of an individual drop.

Analysis of the expression (1), taking into consideration dependence of N and θ_1 on the magnetic field values obtained by visual observation of structures formation confirms probability of magnetization peculiarities availabilityreceived during the experiment. It should be noted, that such peculiarities had not been observed at magnetization of the magnetic fluid itself, which promoted formation of the magnetic emulsion through dispersion.

Temperature and concentration measurements of the emulsion magnetic susceptibility have also been performed. It was established, that dependence of the magnetic susceptibility on volume content of micro-drops shows non-linearity even at concentration $\theta = 3\%$, and thermal dependence of the emulsions magnetic susceptibility follows the law of the type: $x=C/(T+T_o)$

Analysis of the experimental results with consideration to the drops' demagnetization fields of the emulsion allows to get additional information on the proccesses of interaction of unidimensional dispersed particles in the emulsified magnetic fluids.

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DISCONTINUOUS VARIATIONS OF OPTICAL SCATTERING ON FERROFLUID AGGLOMERATE MAGNETIC DROPS

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Ferrofluid agglomerate magnetic drops based on various types of magnetic fluids are of great interest as high sensitive to external magnetic field elements because magnetic instabilities of agglomerate magnetic drops occur in a weak field beginning with the threshold field ~ 1-5 Oe [1,2]. When the interfacial tension is too small both dc and ac magnetic field can induce the multiple scissions of agglomerate magnetic drops in thin films of magnetic fluid [3]. With the decreasing of the film thickness the threshold fields of scissions decrease too. That is why to obtain a sample with high field sensitivity it is worth to use very thin films and magnetic fluids with very low interfacial tension value [3]. We used the plane samples with thickness of about 10 microns.

The liquid of principal interest comprised magnetite particles in kerosene with volume fraction of magnetite ~ 2%. All the samples contained agglomerate magnetic microdrops when H = 0. The average parameters of the samples are: magnetic susceptibility of agglomerate magnetic microdrops μ~70; interfacial tension $4{,}5*10^{-4}$ dyn/cm (sample 1) and $8{,}5*10^{-4}$ dyn/cm (sample 2).

When magnetic field is applied perpendicular to plane gap a thin sample exhibits an assembly of agglomerate magnetic microdrops arranged on a locally hexagonal lattice [4]. We have studied the changes of hexagonal lattice as function of an applied ac magnetic field with frequencies f varying from 0 to 600 Hz and observed the light scattered by the samples.We observed a locally hexagonal array in our samples through a microscope in the direction of the field and measured the mean distances between nearest neighbours - ℓ.The experimental features of ℓ are: multiple scissions of microdrops result in increasing of microdrops number in the samples thus the mean distance ℓ decreses with increasing of applied field; at film thicness of 10 microns simultaneous multiple scissions of most of microdrops result in discontinuous variation of hexagonal lattice. When the magnetic susceptibility of agglomerate magnetic drops μ~50 the hexagonal array formation begins at H ~ 30 Oe[3], when μ~70 at H ~ 10 Oe.

Fig.1 shows the mean distances between nearest neighbours ℓ versus the applied field. These results were obtained for samples 1 (curve 1) and 2 (curves 2 and 3) at f= 200 Hz (curves 1, 2) and f= 300 Hz (3).

At carring out scattering experiments the incident laser beam of He-Ne laser was normal to the film of liquid. Fig.2 shows the angle between the scattared ray and the transmitted ray versus ac magnetic field obtained for sample 1 at f= 0 (curve 1), f= 60 Hz (2) and f= 600 Hz (3).

The threshold changes of anisotropic light scattering is characteristic of very thin samples with thickness of about 10 microns. The threshold field in which the agglomerate magnetic drops split into smaller ones coincides with the threshold field in which the anisotropic light scattering changes. At the same interfacial tension and μ the value of ℓ increases with increasing of the frequency as the threshold fields f scissions increases.

With the decreasing of the interfacial tension the mean distances between nearest neighbours ℓ decrease too at the same frequency of external magnetic field.

Very thin layers of magnetic fluid with agglomerate nagnetic microdrops have a high sensitivity towards the field because multiple scissions of microdrops result in threshold changes of hexagonal lattice and scattering pattern in both dc and ac magnetic field normal to the film plane.

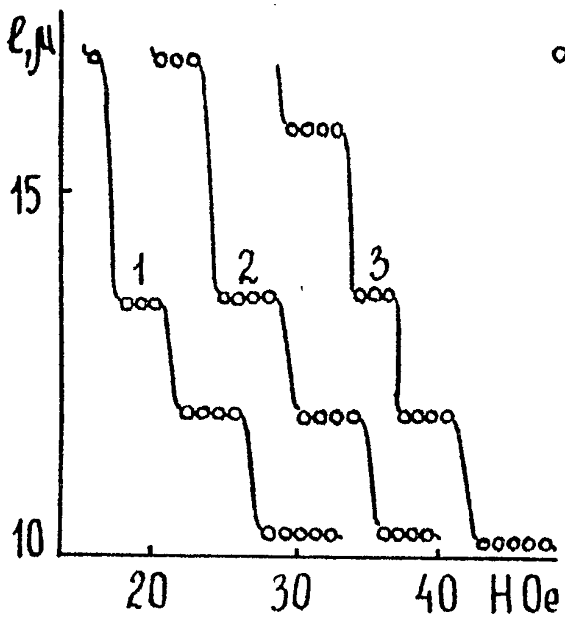

Fig. 1.

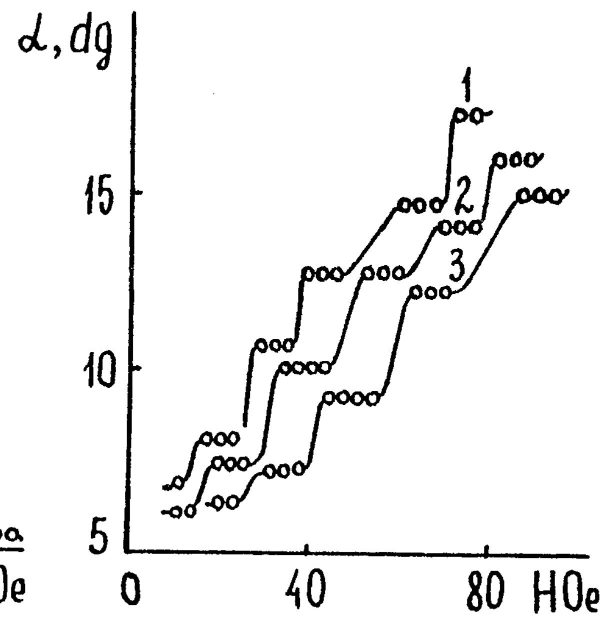

Fig. 2.

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MAGNETIC GRANULOMETRY OF POLYDISPERSE COLLOIDS AND INTERACTION BETWEEN PARTICLES

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By decomposition of magnetization curve of colloid on sum of Langevin functions with different moments m_i :

$$M(H) = \sum n_i m_i L(Hm_i / kT) \qquad (1)$$

it is possible to calculate the spectrum of magnetic moments in colloidal dispersions [1]. The analysis of real magnetization curves of various of magnetic colloids show that the form of m distribution curves depends on the specifics of magnetic fluid technology as well on condition of particle chemical composition and coprecipitation conditions. The bimodal magnetic moment distribution curves have been observed in colloids containing chemically coprecipitated complex ferrite particles [2].

Above mentioned analysis does not take into consideration any interaction between particles, but this question exists. In order to include magnetic interaction in the analysis it is suggested to replace a simple magnetization model of colloids (1) by a more complicated, which concretize the magnetic field value the Langevin parameter is calculated for. One of the possibilities is to perform magnetogranulometric analysis employing the idea of a local field. According to the mean field model [3], instead of (1) the magnetization curve is expressed by the following formula:

$$M(H) = \sum n_i m_i L\big(m_i (H + \lambda M) / kT\big) \qquad (2)$$

By assuming independence of local field parameter λ from temperature, the value of this parameter may be determined experimentally from temperature dependence of the initial magnetic susceptibility and magnetic saturation of concrete sample. Using this value λ it is feasible to perform magnetogranulometric analysis accounting for particle interaction effects. Results for ferrite particles containing colloids are presented in this paper.

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THE INFLUENCE OF MAGNETIC INTERACTION IN THE CURVES OF MAGNETIZATION

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In the present paper the curves of magnetisation are numerically simulated considering polydispersion and magnetic interaction in magnetic fluids in the approximation to average field model[1]. The influence of local field's parameter in the curves of magnetisation under the different dispersion of subdomain magnetite particles is investigated.

In average field model the reference of magnetic interaction as:

$$M(H_{ef}) = L(H + \lambda M), \tag{1}$$

where λ -parameter of interaction, H- the external field, L-function of Langevin. As function of dispersion the logarithmically normal low is [2]. When calculating the equation has been determined in each point as the following [3]:

$$M^* = \frac{\int_a^b L(\xi^*) f(m^*) d(m^*)}{\int_a^b f(m^*) d(m^*)}, \text{ where } M^* = \frac{M}{Ms}, \quad \xi^* = (H^* + \lambda M^*)\left(\frac{m}{100 m_0}\right), m_0 = \langle m \rangle \tag{2}$$

The relation with real values as:

$$H^* = \frac{100 m_0 H}{kT}, \quad \lambda^* = \frac{100 \lambda m_0 Ms}{kT}, \quad m^* = \frac{m}{m_0}, \quad f(m^*) \text{ - function of dispersion.} \tag{3}$$

The number 100 and border of integration (a,b) don't have certain physical meaning, however are input for making the calculation possible. The results in graphs are presented for easier demonstration as the ration of fluids magnetisation to the external field.

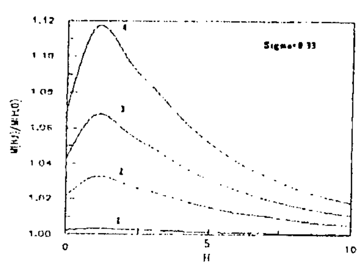

Fig.1

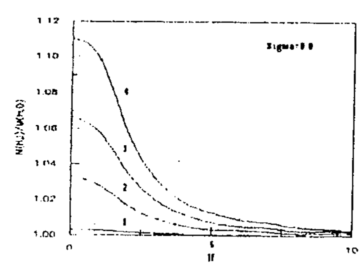

Fig.2

In the graphs: Sigma - parameter of dispersion(Fig.1 Sigma=0.33, Fig.2 - Sigma=0); 1-λ =0.01, 2-λ=0.1, 3-λ=0.2, 4-λ=0.33.

According to total results the area of the maximum interaction is in low the external field. It is possible that the results will help to improve the method of magnetic granulometry.

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ON THE EQUATION OF FERROFLUID MAGNETIZATION

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The equation of ferrofluid magnetization in the presence of ferroparticles aggregates has the following form /1/:

$$M = m_1 n_1 L(\xi_e); \quad \xi_e = m_1 (H + \lambda M)/(kT\nu); \; n_1 = (c_1 \rho / M_1). \tag{1}$$

Here M is the ferrofluid magnetization; n_1 is number of ferroparticles per unit of volume; c_1 is mass concentration of ferroparticles, which is assumed to be a constant; m_1 is the magnetic moment of a single ferroparticle; M_1 is its mass; T is temperature; H is magnetic field strength; k - the Boltzmann constant; L - the Langevin function; λ - effective field parameter; ν^{-1} - the everage number of particles in aggregate.

The equilibrial dependences of λ and ν on constitutive parameters of equilibrial state are determined from the equations: $Q^{(\lambda)} = 0$, $Q^{(\nu)} = 0$, where $Q^{(\lambda)}$ and $Q^{(\nu)}$ are the generalized thermodynamic forces of relaxation type:

$$Q^{(\lambda)} = -\frac{\partial f}{\partial \lambda} + \frac{M^2}{2\rho}; \quad Q^{(\nu)} = -\frac{\partial f}{\partial \nu} + \frac{n_1 kT}{\rho}\left[ln \frac{sh\ \xi_e}{\xi_e} - \xi_e L\right]; \tag{2}$$

$f = f(\rho, T, \lambda, \nu)$ is mass density of nonequilibrial thermodynamic potential of the system in absence of magnetic field.

Keeping in the f expansion in a series on parameters λ and ν the addends of second order and neglecting the interaction of these parameters in a zero field, from (2) we obtain:

$$\lambda = \lambda_0(\rho, T) + \lambda_1(\rho, T) M^2; \quad \nu = \nu_0(\rho, T) + \nu_1(\rho, T)\left(ln \frac{sh\ \xi_e}{\xi_e} - \xi_e L\right); \tag{3}$$

The magnetization curves, describing by the equations (1) and (3), are investigated in the assumption that the medium is paramagnetic in small fields, so as $m_1 M_s \lambda < 3kT\nu$, where M_s - the ferrofluid saturation magnetization. It is shown, that for

present instance side by side with the ordinary (monotone convex) forms of the magnetization curve for some values of parameters λ_i, ν_i (i=0,1) the curves with the bend point and one or two points with vertical tangent exist; the function $M(H)$ is multiciphered and two or three values of the magnetization correspond to every value of the magnetic field strength from some interval.

For ensuring of fluid stability at given ρ, T and H the conditions $\partial B/\partial H > 0$, $\partial Q^{(\lambda)}/\partial\lambda \le 0$, $\partial Q^{(\nu)}/\partial\nu \le 0$ are necessary. The stability region of the medium in parameters λ_i, ν_i (i=0,1) space is derived.

The obtained magnetization curves are compared with experimental data /2/. For experimental curve (Fig.2 /2/) we obtain the values

$$\lambda_0 = 4.88;\ \lambda_1 = -1.09\ 10^{-4};\ \nu_0 = 0.995;\ \nu_1 = -0.011,$$

which minimize the expression $\delta = \sum_{i=1}^{N} [M'(H_i) - M'_i]^2$, where (H_i, M_i), i= 1,N - the experimental points, $M' = M/M_s$.

It is shown, that in comparison with the case λ = constant the proposed model of ferrofluid allowes essentially to decrease the divergence between the theoretical and the experimental curves of magnetization at the initial interval of magnetic field strength values ($H < 400$ Oe), i.e. in that region, where this divergence is most great.

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METHOD FOR MEASURING RELAXATION TIME OF MAGNETIC FLUID MAGNETIZATION

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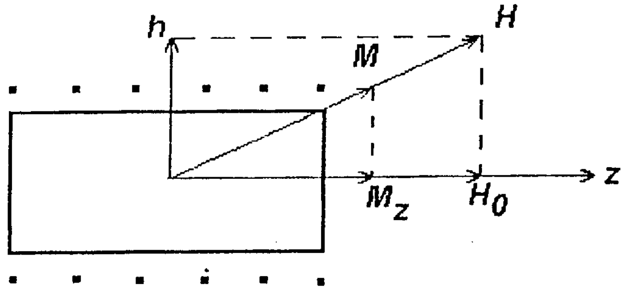
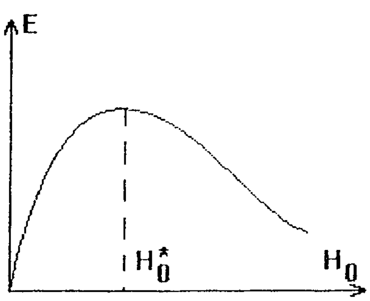
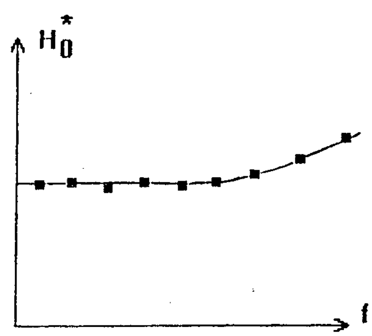
The method bases on crossed magnetic fields. Cylindrical cuvette containing magnetic fluid (MF) is subjected to two fields, the constant one H_0 is parallel to cuvette axis z , and variable one $h = h_m \sin \omega t$, which is perpendicular H_0 . Vectors of resulting field H and magnetization M of MF thus oscillate about z-axis. M_z-projection is varied



at the frequency 2ω. It leads to the arising of emf E in wire coil wound around the cuvette. $E(H_0)$ dependence is presented by a curve with a maximum at $H_0{}^*$. The increase of frequency $f = \omega / 2\pi$ gives rise to retardation of M with respect to H. Maximum of the curve $E(H_0)$ is shifted towards higher field H_0 .





The relaxation time τ of M is calculated from displasement $H_0{}^*$ at some
used
high frequency from $H_0{}^*$ at low frequencies. It is formula received by M. I. Shliomis.

ACCOUSTIC MAGNETIC EFFECT - THE ELASTIC OSCILLATIONS OF THE CYLINDRICAL SHELL-MAGNETIC LIQUID SYSTEM PROBATION

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The frequency and concentration dependence of the elastic oscillations propagation velosity in the magnetic liquid (ML)-cylindrical shell system was investigated. The probation was made with a help of specially made ML- interferometer consisting of vertical glass tube filled in with ML, along which the measuring bundle moves.

The action of our device is based on the Accoustic Magnetic Effect (AME), which is the phenomena of the alternating electric field and electromotive force inducing in the circuit when the accoustic wave propagates in the magnetized ML and oscillations of demagnetizing field intensity does not compensate completely changes of liquid magnetization. The dependence of induced electromotive force amplitude from the magnetizing field intensity (AME field dependence) is closed to Langeven function in the superparamagnetic gas approximation as with collinear so with one-to- one ortogonal wave vector and magnetizing field intensity orientation. The standing wave being emerged simultaneously with the propagation of plane longitudinal wave is repeated by the ferroparticles concentration and ML magnetization along the ML-column. Therefore AME allows the immediate probation of wave by the inductive data unit, stored outside the resonator and interferometrical definition of sound velosity in the ML. The advantages of the given method includes the hindrance absence made by a microphone [1..3].

The presence of the essential dispertion having the resonance nature in the ML- thin- shelled pliable cylindrical resonator system with a help of the ML- interferometer is shown. The divergence between the experimental data and the existing theory of sound propagation in tubes conclusions is founded [1].

In the number of thick- walled tubes under definite frequencies the standing wave with the anomalous large wave length apparently formed as a result of interferention is observed. One of the interpretations being worked out now is the propagation of wave in the system with the velocity exceeding for several times the velocity of sound in the free medium.

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THE EFFECT OF THE ULTRASOUND ON THE PROPERTIES OF THE MAGNETIC LIQUIDS

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The possibility of the magnetic liguids application as the working medium in the acoustomagnetic transformers of vibration energy sets before the investigators the tasks of studying of the powerful ultrasound effect on the structure and properties of the magnetic liquids. The results of the ultrasound effect on the parameters of the curve for the magnetization of the magnetitive magnetic liquids on the basis of kerosenc. For the ultrasound treatment of the magnetic liquids the standard technical sets were used. The value of the magnetic liquids magnetization was determined by the ballistic method in the field of direct current electromagnet FL-1, for which the graduation graphics and interpolar functions of the dependence of the magnetic field intensity on the current value of magnetization were obtained. The mathematical treatment of the graduation and the curves of the magnetic liquids magnetization was conducted on the personal electronic computer by the least squares method.

The comparative analisis of the singletyped curves of the magnetization shourd that after the effect by the small power ultrasound the state of the saturation after the magnetic liquid magnetization is obtained in the original soundless state. So after the treatment of the ampoul with the magnetic liquid 16 (the concentration of the magnetic phase is 16,6%) it was found the values decrease of the saturation after the magnetization from 93 till 88 kA/m and the decrease of the original magnetic susceptibility from 4,26 till 3,46.

The increase of the ultrasound power causes the qualitive change of action for the field dependences of magnectization, which are determined by the concentration of the magnetic phase in the magnetic liquid. As for the patterns of the magnetic liguid 3 but it was observed the decrease in the saturation magnetization from 14,7 till 11,79 kA/m and the original susceptibility from 0,61 till 0,48.

So it was established, that the effect of the powerpul ultrasound on the system of the dispersed magnetic particles in the magnetic liquid causes the change of the kinetics of process and the parameters of magnetization of the magnetic liquids that probably is connected with the structure change of the magnetic liquid.

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MAGNETODYMANIC BEHAVIOR OF A FERRONEMATIC LIQUID CRYSTAL

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Ferronematics (FN) is the term designating suspensions of single-domain ferroparticles in nematic liquid carriers. One may call them the second generation of complex fluids, since those systems are mixtures of media each of which is already complex, viz. nematic liquid crystals and magnetic fluids. This crossbreed produces an interesting class of disperse systems, now existing in both lyotropic [1] and thermotropic [2] forms.

The dynamics of FN is now yet at the very beginning of its development. However even the first published observations [3] show that the orientational response of those systems is a result of a superposition of several, differing greatly, relaxation rates each with its own dependence on the strength of the applied magnetizing field.

Our goal is to find a way to understand some characteristic features encountered experimentally. The starting point is the proposed in [4] expression for the free energy density of FN taking into account the finiteness of the anchoring strength of a liquid crystal on the surfaces of the dispersed particles. This description holds as long as the volume concentration φ of the magnetic particles exceeds the reference threshold value φ_* thus imparting to FN the *collective* orientational behavior—see [5,4].

As a particular problem we consider a FN sample confined inside a plane horizontal layer of thickness D bounded by solid walls. The layer is infinite in the coordinate plane xOy. Planar boundary conditions along Ox at both layer walls are imposed on the nematic. The anchoring on the particle surfaces is supposed to favor the alignment of the grains with the local director. The external magnetic field $\boldsymbol{H}_0$ is applied along the Ox axis. In result, in the initial unperturbed state vectors $\boldsymbol{n}$, $\boldsymbol{m}$ and $\boldsymbol{H}_0$ form a mutually parallel triad and are uniform over the sample.

This equilibrium texture is perturbed by a magnetic field $\boldsymbol{H}_1$ directed in the plane of the layer perpendicular to $\boldsymbol{H}_0$, i.e., along Oy. The induced orientational configuration may be then presented as

$$\boldsymbol{n} = [\cos\varphi(z), \sin\varphi(z), 0] \,, \qquad \boldsymbol{m} = [\cos\psi(z), \sin\psi(z), 0] \,. \tag{1}$$

In the developed model, the complete relaxational response emerges as a superposition of three different processes. In the order of increase of the value of characteristic times they are:

- the rotation of the particles with respect to the matrix, i.e., the motion $\psi(t)$;
- the reorientation of the liquid-crystalline matrix, i.e., the motion $\varphi(t)$;
- the creep of the orientation direction at the layer boundaries, i.e., the motion $\varphi(t)|_{\pm D/2}$.

For the decrements of those processes simple formulas are available which deliver their dependences on the magnetizing field strength H. For example, the rate of rotation of magnetic particles is

$$\lambda_1 = \tau_m^{-1}(0)\,[1 + H_0/H_a]\,, \tag{2}$$

and for the rate of the carrier reorientation

$$\lambda_2 = \tau_n^{-1}(0)\,[1 + \varphi H_0/\varphi_*(H_0 + H_a)]\,. \tag{3}$$

Here H_a is the effective magnetic anisotropy field exerted on the particles on the part of the liquid crystal. In the framework of the developed approach one gets explicit expressions for the initial (at $H_0 = 0$) relaxation times $\tau_m(0)$ and $\tau_n(0)$ and the amplitude H_a through the material parameters of the system.

In a harmonically oscillating probing field $H_1 = H_1 e^{i\omega t}$ the obtained equations of motion transform into a non-homogeneous set

$$\left(i\omega\tau_n + 1 + \frac{f}{f_*}\right)\varphi - \frac{f}{f_*}\,\psi = 0\,, \qquad \left(i\omega\tau_m + 1 + \frac{H_0}{H_a}\right)\psi - \varphi = \frac{H_1}{H_a}\,. \tag{4}$$

Making use of the smallness of parameter τ_m/τ_n, one gets the solution of the Eq. 4 in the form

$$\begin{aligned}\varphi &= \frac{fH_1}{f_*H_a}\left\{\frac{1}{\left[1 + \frac{H_0}{H_a}(1 + \frac{f}{f_*})\right](1 + i\omega\tau_1)} - \frac{\tau_m}{\tau_n}\cdot\frac{1}{\left(1 + \frac{H_0}{H_a}\right)^2(1 + i\omega\tau_2)}\right\}, \\ \psi &= \frac{H_1}{H_a}\left\{\frac{f}{f_*}\cdot\frac{1}{(1 + \frac{H_0}{H_a})\left[1 + \frac{H_0}{H_a}(1 + \frac{f}{f_*})\right](1 + i\omega\tau_1)} + \frac{1}{(1 + \frac{H_0}{H_a})(1 + i\omega\tau_2)}\right\}.\end{aligned} \tag{5}$$

The field-dependent relaxation times entering Eq. (5) are defined through the decrements (2) and (3) as $\tau_\alpha = 1/\lambda_\alpha$.

As it follows from the definitions (1) of the angles φ and ψ, the first of them describes the orientational (director distortion), and the second—the magnetic response of the sample. However the behavior of each angle is a result of an interplay of both magnetic and orientational modes which means the presence of two relaxational maxima in the frequency spectra of the system. The low-frequency one is associated with the director motions, and the higher-frequency one—with the particle rotations. To the most extent those peaks must be pronounced in the magnetic susceptibility since the weight coefficients of the modes for ψ are of the same order of magnitude. The carried out numerical estimates are in reasonable agreement with the reported results [3].

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PROBLEMS FOR SYNTHESIS OF ULTRA-DISPERSE MAGNETITE FROM AQUEO-ORGANIC MEDIA AND RHEOLOGICAL PROPERTIES OF MAGNETIC COLLOIDS ON THEIR BASIS

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The most wide it is spread a method of magnetite synthesis by coprecipitation of divalent and trivalent iron ions in ammonium hydroxide. Together with magnetite obtained by this traditional method it was used for magnetic fluid (MF) preparation a magnetite synthesized of aqueo-organic media: -acetone, -dioxane, -acetous what allows to control solid-state parameters of particles, their shape, size, dispersity, anisotropy as well as rheology of colloid as a whole. Magnetite powders of above mentioned modifications were used for colloids preparation on basis of polyethylsiloxanic(PES-4) carriers (MK-2-40 type) and transformer oil (MK-8-40 type) with oleic acid as a surfactant.

According to X-ray phase analysis data, in all cases it was obtained magnetite. Accoding to Mossbauer spectroscopy/1/ magnetite cristallites from aqueo-organic media differ by their structural state from usual aqueous magnetite by size, structure and cristallo-chemical state of their adjacent surface layer,more perfect cristal lattice and minimal defects of the cristall latter in adjacent surface layer (near-to-surface particle layer) what promotes a very significant changes at surfactant adsorption and to a considerable extent it determines physico-chemical properties of colloid as a whole.

Hitherto in literature the question of effect of magnetite surface structure properties and its modifacation on magnetic fluid rheology wasn't investigated, what is evidently caused by the fact at present many aspects of this problem for colloidal systems in non-aqueous solution aren't worked out sufficially.

Of interest it is establisment of rheology correlation at varying of magnetite surface modifacation. Investigations are carried out on rotative magnetoviscometer/2/ which allows to carry out measurements both in uniform und in nonuniform magnetic field. Measuring unit is installed in temperature control chamber of standard viscometer of type Polymer-M. Studies of MF rheological properties were carried out also on rotative viscometer Rheotest-2.

In Fig.1 given obtained rheograms of colloids MK-2-40 (without magnetic field effect, curve 1 - aqueo-acetone modification of magnetite, 2 - aqueous, 3 - acetous, 4 - dioxane). It is found that aqueo-acetone modification for MK-2-40 and -acetone and -dioxane modification of magnetite for MK-8-40 allow to retain Newtonian properties of colloid over the whole range of studied shear speeds. In Fig.2 given rheograms of MK-8-40 (at magnetic field effect for aqueous (curve 1 - H=0 and curve 2 - H=400 kA/m) and aqueo-acetone modification of magnetite (curve 3 - H=0, curve 4 - H=400 kA/m)). Generally used aqueous and aqueo-acetous modifacations introduce in magnetorheology essential non-Newtonity and effective viscosity shows one-to-one tendency to reduction with shear speed increase due to colloid structure change.

On Fig.3 it is given concentration dependence of magnetic colloids effective viscosity with magnetite usual aqueous modification (curve 1) and magnetite modification of aqueo-organic media (curve 2). Just as it was to be expected, at the same con-

centration magnetic fluids with magnetite aqueous modification have increased viscosity, at solid phase concentration of above 6...8% it is observed sharp rise of viscous characteristic and it is reached ultimate concentration level corresponding to beginning of structure formation.

In case of magnetic fluids with magnetite modification of aqueo-organic medium, there is no such a mechanism, this threshold is sheared to a region of higher concentrations and curve is more gentle (Curve 2).

For MK-8-40 colloid on base of transformer oil, aqueo-acetone and -dioxane magnetite modification allow to retain Newtonian properties of colloid over the whole range of studied magnetic fields in the interval of disperce filler concentration to φ_S = 22% and only at solid phase concentration of 27% it appears visible pseudoplasticity. For MK-2-40 it is observed Newtonian behaviour of colloid in the interval of solid rhase concentrations of $\varphi_S \leqslant 17...18\%$ over the whole range of homogeneous magnetic field.

Studying of nonunifirm magnetic field effect on dynamics of rheological properties changing with gradient of 30 and 70 Tl/m showed MK-8-40 rheological curves with usual aqueous modification of magnetite assume essentially non-Newtonian character with sharp increase of yield limit while for colloid of aqueo-dioxane and -acetone modification it is observed viscosity increase at retain of Newtonian behaviour. It may suppose this fact is critical one at estimation of colloid serviceability in magnetic fluid seals (MFS).

Thereat, undoubtedly colloids retaining Newtonian character of rheology both in uniform and in nonuniform magnetic fields are preferable. Thus, it can conclude hitherto disregarded possibilities of directed control of colloid physico-chemical properties when varying of magnetite surface modification by aqueo-organic media, possess a great potential in adjusting region of structure-rheological properties of MF on different carrier liquids. New colloids retain Newtonian properties in enlarged range of concentrations and applied external magnetic field, differ by lower viscosity and small magnetic viscosity effect (MVE) what is evidence of excellent operational possibilities to optimizate MFS characteristics.

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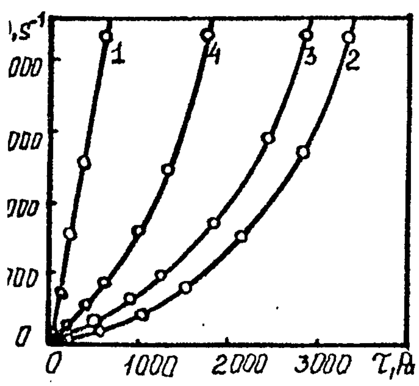

Fig.1

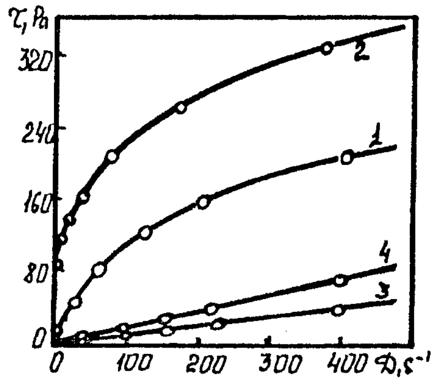

Fig.2

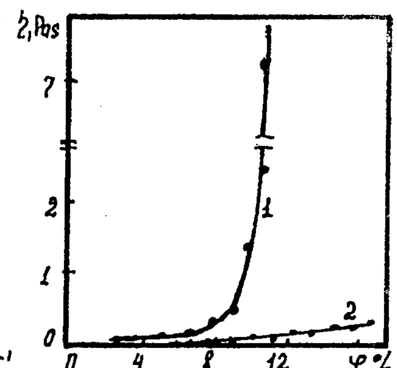

Fig.3

PHYSICO-CHEMICAL ASPECTS OF MAGNETIC COLLOIDS SYABILITY PROGNOSTICATION

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To a considerable extent, the problem of magnetic colloid stability is stipulated by the fact that for such systems it is in essence typical the possibility to redistribute discrete magnetic particles in carrier-liquid in spatio-nonuniform fields of forces (magnetic, gravitational, temperature, centrifugal etc.) and possibility to change physico-chemical properties thereat.

Hitherto the main directions of magnetic fluids colloidal stability increase came, from one side, to selection additional surfactants of multifunctional purpose, and, from another side, to load MF with special agents and fillers (antiwear, anticorrosion, anti-oxidant etc.) and to remove aggregations of disperse particles.

Problems of creation and investigation of magnetic fluids at modifying physico-chemical and surface properties of disperse magnetite filler itself as one of the main directions for increasing of colloids stability are not raised hitherto in spite of its evident actuality. In this paper attention is given to looking for additional possibilities of colloid stability increasing on account of aimed adjusting of physico-chemical properties of disperce magnetite synthesized from different aqueo-organic media by chemical coprecipitation of divalent Fe^{+2} and trivalent Fe^{+3} iron ions and to problems of their combination with various kinds of carriers-liquids at a fixed surfactant - oleic acid.

It is carried out complex analysis of colloids quality and stability parameters on basis of MF magnetic and magnetorheological properties, analysis of time-dinamics of operation-thechnical characteristics change in nonuniform magnetic field: punch pressure in the model of magnetic fluid seals(MFS) and friction torque. Measuring of friction torque was carried out on rotative magnetoviscometer of colloid type which allows to carry out measurements both in uniform und in nonuniform magnetic field /1/. Measuring of static magnetization of MF was carried out by pulse-inductive technique. Measuring of initial susceptibility was being carried out on parametric facility on basis of reciprocal inductance bridge.

Analysis of magnetic properties within mean spherical approximation in weak fields and a model of field efficiency in asymptotics allows to determine a range of structural parameters of magnetic colloid quality. On basis of comparative approximation of MF polidispersity by means of Gamma-distribution /2/ taking into account interparticle interaction it is possible to define more exactly relations between concentrations of magnetic rhase φ_m, solid one φ_s, hydrodynamic one φ_h for colloid particles. Furthermore, it is determined asymmetry coefficient γ_1 and excess one γ_2, specifying part of "large particles tail" in colloid stability under magnetic field effect. On basis of this analysis it is found concentration dependence of initial susceptibility and magnetic properties for each type of colloids (MK-2-40, MK-8-40 produced in our laboratory), mean field constant λ, magnetic anisotropy constant K_a /3/ and specified "coupling function" $\Psi(\sigma)=(3/4\sigma)\cdot(\sigma^{1/2}\cdot\exp(\sigma)/\Phi(\sigma^{1/2})-1)-1/2$ with the "coupling integral" $\Phi(\sigma^{1/2})=\int\exp(x^2)dx$ /4/, where the "coupling parameter" is given by $\sigma_a=K_aV_m/k_bT$.

It was studied effect of magnetite modification synthesized from aqueo-organic media on MF stubility. It was established that the most stable colloids are colloids of aqueo-acetone and aqueo-dioxane modifications, for acetous ones is typical formation of the most small particles with high degree of ellepticity.

Among technique which are used for MF stability diagnostics a special place take half-empirical methods of modelling colloid state adequate by effect of value and gradient of magnetic field as a main destabilizing factor: diagnostic technique by punch pressure in inhomogeneous field of MFS in dependence on time and diagnostics method by time dependence of friction torque (magnetoviscometer with profiled pole pieces for inhomogeneous magnetic field formation /1/).

Whan analysing obtained experimental data of time dependence of punch pressure $\Delta P(t)$ and one of friction torque $M^{fr}(t)$ it were proposed the following approcximating relations (approximation models): $\Delta P(t)=\Delta P_o+(\Delta P_m-\Delta P_o)\cdot(1-\exp(-\alpha\cdot t^{0.5})$, $M^{fr}(t)=M_o^{fr}+(M_m^{fr}-M_o^{fr})\cdot(1-\exp(-\beta\cdot t)$, where ΔP_o - initial punch pressure found by approximation of experimental dependence $\Delta P(T)$ to region of small times ($0<t<10^4$ sec) within the limits of Taketomi's model $\Delta P(t)=\Delta P_o\cdot(1+K_t\cdot t^{0.5})$ with colloid stability coefficient K_t /5/. Maximal pressure ΔP_{max} and α was found by approximation of finite time curve part $\Delta P(t)$, $15<t<500$ min. In the same way, parameters M_o^{fr}, M_{max}^{fr}, β were found by approximation of initial and finite time part of obtained experimental dependence $M^{fr}(t)$. It were calculated parameters of MF colloidal stability determining the period of its serviceability (as conditional life time T_{MF}).

It was studied concentration dependence and modification effect of magnetite synthesized from aqueo-organic media (aqueo-acetone, -dioxane, -acetous) in comparison with uselly used aqueous one) on colloid stability in nonuniform magnetic field. It was found the highest stability and optimal characteristics possess magnetic fluids MK-2-40 (carrier-liquid - polyethylsiloxane PES-4) on aqueo-acetone modification of magnetite. For magnetic colloids MK-8-40 (carrier-liquid - transformer oil) it is the most optimal to use magnetite synthesized from aqueo-acetone and aqueo-dioxane modification of magnetite. The latter possesses the most high stability. In table there are given main parameters of quality and conditional coefficients of stability found in limits of above-mentioned methods correlating between themselves.

MF	Magnet. type	Magnetiz. sat., kA/m	Density g/sm^3	Viscos. Pa·s	K_{stab}^{punch} %	Ψ	K_{st}^{fr}	Cond. life time, T_{mf} 10^3
1	aqueo-acet	47.	1.435	0.117	9.1	0.051	0.67	2.09
2	aqueous	46.5	1.394	0.59-0.16	12.4	0.122	1.18	1.74
3	aq-acetous	46.7	1.423	0.35-0.22	20.4	0.046	1.26	1.56
4	aqueo-diox	47	1.435	0.11	11.3	0.042	1.15	2.159

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LINEAR AND NONLINEAR REGRESSION PROBLEMS ORIGINATING IN MAGNETIC FLUID INVESTIGATIONS: APPROACHES TO NUMERICAL TREATMENT

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The inevitable solid phase polydispersity of magnetic colloid causes physical properties of the latter to deviate from corresponding theoretical predictions, providing, of course, that the measurements have been performed with due accuracy. The polydispersity can, however, be taken into account, this leading mainly to the necessity to perform a regression analysis during (or even before) the processing of experimental data. A reliable and (at least relatively) fast-working procedure for such analysis would be an extremely useful instrument allowing one to determine magnetic particle size distributions in a magnetic fluid without using of electronic microscopy. But, mathematical contents of the problem being a Fredholm equation of the first kind, the desired procedure (except for some very special cases) proves hard to design. The outcoming solutions are known for their instability; and the situation grows worse if special conditions must be imposed.

In the present paper several solving methods for regression problems such as described above are discussed. A relatively new concept of imposing constrains on regression parameters has been developed [1]. Its main idea is to modify the fitted function itself leaving the solving procedure and form of residual expression (i.e. objective function) unchanged. This influences in a natural way the behaviour of regression in the 'allowed' domain, too. Nevertheless, the modification appears to have good regularising properties; in certain cases the algorithm becomes completely insensitive towards the initial length of iteration step.

Although the principal attention has been paid to the solving process of linear regression problems, ideas similar to that described above can be used in the nonlinear case, too. Levenberg-Marquart-type algorithms, which are in some cases the only sensible way to a solution, remain fully applicable even if the most unnatural conditions are to be imposed. The modifications made in the fitted function still display their regularising effect on the solving process.

The algorithms presented in this paper have been developed for magneto- optical measurements [2], but they can be applied to many other problems where regression analysis, at least with homogeneous regression term, is involved.

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MICROWAVE AND ULTRA SOUND METHODS OF SIZE DETERMINATIN OF FERROMAGNETIC PARTICLES AND AGGLOMERATES IN MAGNETIC FLUID

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The magnetic fluid placed into the constant magnetic field change an internal structure, which is connected with the agglomerate formation of ferromagnetic particles. For property and behavior description of this structure it is necessary to have a knowledge about the ferromagnetic particles volume, the size and the shape of agglomerates.

It was shown that the size of ferromagnetic particles may be determined by the resonance dependence of the reflection coefficient of microwave radiation from magnetic fluid. The reflection coefficient has been chosen as the information parameter that permits to reduce the influence of frequency features connected with the phenomenon of microwave radiation interaction with the layer of magnetic fluid, filling the section of rectangular waveguide. The magnetic fluid layer has been chosen to be of such thickness so that in spite of slight absorption of microwave radiation the reflection influence from back surface of magnetic fluid layer on reflection coefficient dependence on the value of magnetic field has been removed. The magnetic fluid was held up in the waveguide with the dialectical insertions which are transparent in the microwave band. The waveguide of standard profile (0.34 * 0.72) cm with the magnetic fluid was placed between the poles of electromagnet.

It was shown that the reflection coefficient dependence on the value of magnetic field, which has typical resonance features, coincides with the resonance dependence of the active part of the dynamic magnetic susceptibility on frequency. The size of ferromagnetic particles was determined by the dependence of ferromagnetic resonance curve width on the frequency of microwave radiation. The microwave radiation frequency influence on the band of ferromagnetic particles determining sizes has been analyzed.

To investigate the magnetic fluid structure placed into constant magnetic field the method of agglomerate observation in ultra sound band has been suggested, which allows to visualize the process of agglomeration in the volume of magnetic fluid as distinct from optical methods used for the investigation of magnetic fluid thin layers, whose properties and structure differ from those for volume.

For the method realization the scanning radiation at frequency 5 MHz reflected from the volume of magnetic fluid, placed between the poles of electromagnet was detected by analogy-digital converter and was analyzed by a processor. The results of processing was displayed on the monitor screen. The magnetic field was changed from 0 to 2000 Oe. With the value growth of magnetic field the cigar-form agglomerates appeared stretching in the direction of field and their subsequent growth with the magnetic field increasing was observed.

We compared the curves of the temperature dependence of threshold magnetic field (at which the formations of agglomerates begin) received by the scanning radiation and optical dispersion method. The size and shape of ferromagnetic particles agglomerates have been measured in dependence on temperature and the value of magnetic field.

The methods suggested allow to make the experimental investigation of the internal structure of the magnetic fluid volume in constant magnetic field and to investigate the property differences of thin layers and magnetic fluids volume.

INFLUENCE OF THE SHF-FIELD ON THE MAGNETIC PROPERTIES AND COMPOSITION OF FERROMAGNETIC FLUIDS

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The influence of the superhigh-frequency electromagnetic field (SHF) on the magnetic properties and composition of ferromagnetic fluids (MF) has been investigated.

The ferromagnetic fluids were obtained by means of the chemical precipitation of the high-dispersion iron oxide (II,III) with its subsequent peptization in the solution of oleic acid in mineral oil.

The MF sampels to be investigsted were place in the SHF electromagnetic field (λ=3.2 cm) in the area of maxima of the electric and magnetic component of the field. The electric field intensity was 2×10^4 V/m, the magnetic field intensity was 40 A/m. The dimensions of the rectangular resonator were 10×21×44 mm. The power of the generator was 6 W. The round diaphragm was used as an element of communication between the resonator and wageguide. The time of influence was 5 minutes.

The constancy of the volume content of the ferromagnetic phase in the solid phase of the MF sampels investigated after the influence by the SHF field (see table) indicated that the super-frequency electromagnetic field does not influence the ferromagnetic phase structure at the level of the cristal lattice. The analysis of the dependence $\chi_m(H)$ obtained by the methods states in [1] allows to suppose that the influence of the SHF field causes the strucural changes associated with the interparticle interaction in iron oxide (II,III). The increase of the characteristic field H_c expressed more clearly for the sample placed to the maximum of the SHF field electric component is conditioned evidently by the change of the structure of the ferromagnetic particles and, particularly, by the increase of their anisotropy.

According to the data of the electron microscopy in the MF samples subjected to the SHF influence, the large shapeless formations generated due to the aggregation of the Fe_3O_4 primary particles under the influence of the SHF fields are observed along with the high-dispersion Fe_3O_4 particles the average size of which is 9 nm (for the initial MF sample it is 7.5 nm).

The analysis of the IR spectra indicated that in the samples subjected to the SHF-influence the intensity of the lines characteristic for the groups OH (3300 cm^{-1}) and C=O (1700-1720 cm^{-1}) are increased. It is

caused by the oxidization of the organic components included in the composition of the MF: oleic acid and mineral oil.

Table. Densitometric and magnetostatic characteristics

Sample / Characteristics	Initial MF	MF after influence of the SHF-field in the maximum: magnetic component	MF after influence of the SHF-field in the maximum: electric component
Density, kg/cm^3	1475	1372	1416
Saturation magnetisation, kA/m	46	37	41
Volume content of the ferromagnetic phase in the solid one, %	0.70	0.69	0.70
Initial magnetic susceptibility	4.36	2.90	3.30
Maximum magnetic susceptibility	6.20	4.60	5.10
Characteristic field kA/m	0.70	0.90	1.20

In accordance with the obtained data, the anisotropic aggregates of the Fe_3O_4 particles are formed in the MF under the influence of the super-frequency electromagnetic field (λ=3.2 cm) and the partial oxidization of the oleic and mineral oil are observed that, however, does not cause the disturbance of its aggregative stability.

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DISPERSITY OF NICKEL AND ITS INTERACTION WITH SURFACTANT IN MAGNETIC FLUID

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Producing of the magnetic material (ferrophase) in the form of highly dispersive particles and creating an adsorption layer of the surfactant on their surface are principally important to obtain magnetic fluids [1].

Magnetic fluids studied in the present work were produced by chemical precipitation of metal nickel with its subsequent stabilisation by a surfactant [2]. Hexane and oleic acid were used as a dispersive medium and surfactant respectively.

The aim of the present work was to determine the particles size of ferrophase (highly dispersive nickel) and to study its interaction with oleic acid.

The size and the form of nickel particles were studied by the transmission electronic microscopy. The analysis of electron microscopic data shows that the ferrophase in the studied magnetic fluid is produced by deaggregated spherical nickel particles, which is characterized by a narrow particle size distribution. The maximum of the size distribution curve of nickel particles lies about 12-14 nm.

Products of the nickel interaction with an oleic acid were studied by FTIR-spectroscopy. The main absorption bands observed in FTIR-spectra and their references are listed in the table.

Table.

The main absorption bands in FTIR-spectra of highly dispersive nickel treated by oleic acid

Maximum of the absorption band, cm^{-1}	Reference of band [2-6]
3432	Stretching of H_2O and stretching of O-H groups hydrogen bonded
2956	Antisymmetric stretching C-H of CH_3-groups
2924	Antisymmetric stretching C-H of CH_2-groups
2851	Symmetric stretching C-H of CH_2-groups
1563	Antisymmetric stretching C=O of carboxylate-ion (COO^-)
1410	Symmetric stretching C=O of carboxylate-ion (COO^-)
1328	Stretching C-O of carboxylate-ion (COO^-)
1273	Stretching C-O of carboxylate-ion (COO^-)
970	Deformation C-H of olefins
720	Pendular oscillations of CH_2-groups
670	Deformation fluctuations of C-H of olefins
590	Stretching of Ni-O

The presence of absorption bands of carboxylate ion (1577, 1410, 1328, 1273) in FTIR-spectra of powder-like nickel extracted from a magnetic liquid and the absence of the absorptions of the carboxyl group characteristic of the free (unbonded)

acid (2500-2700, 1700) indicate that while producing a ferromagnetic fluid on the base of highly dispersive nickel its stabilization is accompanied by the formation of the respective salt on its surface.

The peculiarity of FTIR-spectra of the sample under study is the presence of the absorption band 3432 cm^{-1} characteristic of stretching of the O-H group, the intensity of which increases at ageing. It is likely the result of forming hydroperoxides due to oxidation of nickel oleate by the mechanism known for fatty acids [7]. The products of nickel oleate formed on the surface of nickel particles are not surfactant which leads to the disturbance of sedimentation stability of the studied magnetic fluid while storing.

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DYNAMIC PROPERTIES AND MAGNETIC STRUCTURE OF FERROFLUIDS: RESULTS OF MESSBAUER SPECTROSCOPY

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Some ferrofluids over temperature range $100<T<300K$ have been investigated by Messbauer spectroscopy and magnetic susceptibility methods. These materials were stable colloidal suspensions of magnetite particles with mean particle diameter about 10 nm in liquid carriers (kerosene, silicone). Temperature dependencies of Messbauer spectrum parameters: line width G(T), spectrum area S(T) and hyperfine field $H^{I,II}(T)$ (for two positions of Fe^{57} in the magnetite crystal lattice) have been studied.

The dependencies G(T) and $H^{I,II}(T)$ for kerosene based ferrofluids with concentrations of magnetite $0{,}03<\varphi<0{,}16$ over temperature range $130<T<180K$ (that is below freezing-region) have an anomaly at $T=T_g$ and $T_g(\varphi)$ is the increasing function. The curve G(T) has a sharp decrease (step) and $H^{I,II}$ (T) has a small increase (crook) as compared with normal course, when T decreases. This anomaly may be due to transition of the system of particle magnetic moments into the state of "superferromagnetism" or "superspinglass".[1] This transition is not observed for the ferrofluids with the same magnetite concentration, but silicone carriers. It may be connected with different character of aggregation. Diffusion broadening of line $\Delta G(T)$ for all samples was determined at temperature above freezing-region and estimations of diffusion coefficient D have been obtained. Concentration dependence $D(\varphi)$ for kerosene based ferrofluids has maximum about φ 0,07. The comparison of our estimations for coefficient of viscosity $\eta = kT/3\pi D \cdot d^*$ with the data for η obtained by other methods allowed to receive the value of $d^* \approx 100$ nm for investigated ferrofluids. Here d^* is mean diameter of particle aggregate.

As S(T) is proportional Messbauer f-factor, it may be connected with magnetic particle vibration characteristics and with module of elasticity E(T). The estimations of E(T) at temperature above freezing-region have been obtained for all investigated ferrofluids.

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SPIRAL STRUCTURES IN LIQUID-CRYSTALLINE MAGNETIC SUSPENSIONS

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Ferrocholesterics (FC) are new kind of magnetic suspensions in which cholesteric liquid crystal (CLC) is a carrier. The solid phase of a FC consists of single – domain needle - liked ferromagnetic grains incorporated into CLC matrix. Strong anisometricity of a grain gives rise to the close connection between the magnetic moment $\boldsymbol{\mu}$ and the principal axis $\boldsymbol{m}$ of the grain. The most significant feature of such a suspension is existence of spontaneous magnetization in the absence of external magnetic field. Because of the spiral structure of CLC matrix, the magnetization vector $\boldsymbol{\mathcal{M}}$ of a FC rotates around the helical axis with the CLC director $\boldsymbol{n}$, creating a helical structure. In this paper we study orientational and magnetic properties of a FC in a magnetic field which is perpendicular to the helical axis of the spiral structure. We suppose that homeotropic conditions ($\boldsymbol{m} \perp \boldsymbol{n}$) on the grain surfaces take place and the diamagnetic anisotropy χ_a of the matrix is negative.

Magnetic field $\boldsymbol{H}$ normal to the spiral axis leads to the distortion of the FC structure because magnetic grains tend to be oriented along $\boldsymbol{H}$ and the director tends to be perpendicular to $\boldsymbol{H}$ corresponding to negative χ_a. Thus two orientational mechanisms of the spiral untwisting connected with the interaction between the field and magnetic moments of the ferroparticles (dipolar one) and between the field and the diamagnetic CLC matrix (quadrupolar one) do not concure, but act in the same way ensuring the grows of the pitch.

We consider deformation and unwinding of the FC structure in the framework of the continuun theory [1] based on the free energy functional. It is shown that orientational and magnetic properties of the FC are determined by two dimensionless combinations of material parameters. One of them $\xi = M_s f_0/(q_0\sqrt{K_{22} \mid \chi_a \mid})$ operates the regimes of spiral unwinding (if $\xi \gg 1$, the spiral untwisting is realized due to dipolar (ferromagnetic) mechanism, and if $\xi \ll 1$ – due to quadrupolar (diamagnetic) one). The second one $\kappa = f_0 k_B T/(vK_{22}q_0^2) = (p_0/\lambda)^2$ describes the so - called segregation effect [1]: magnetic field $\boldsymbol{H}$ induces the redistribution of the magnetic admixture in the FC, and so the concentration f of magnetic particles increases in those parts of a sample, where $\boldsymbol{m}$ and $\boldsymbol{H}$ are parallel. As a result of strong orientational interaction between the particles and the director, the orientational deformation appears in the region with the spatiel scale λ. Thus, if $\kappa \gg 1$, the effect of magnetic particles segregation is unessential, since $\lambda \ll p_0$. Here K_{22} is the twist elastic constant of the CLC, f_0 is the volume fraction of the particles in the suspension, k_B is the Boltzmann constant, T is the temperature, M_s is the saturation magnetization of the grain, v is the grain volume, q_0 is the wavenumber of the spiral at $H = 0$. The volume fraction of the magnetic admixture is assumed to be sufficiently low ($f_0 \ll 1$), and the interparticle magnetic dipole - dipole interaction is negligible.

The field $\boldsymbol{H}$, being taken in the direction normal to the FC spiral, causes the untwisting of the spiral structure, if the field strength $\mathrm{H} = Hq_0^{-1}(|\chi_a|/K_{22})^{1/2}$ reaches the critical value H_c. Fig.1 shows the dependence $\mathrm{H}_c(\xi)$ for some values of κ. The dashed lines correspond to the limiting cases $\kappa \to 0$ and $\kappa \to \infty$. For $\kappa \to 0$ the concentration of magnetic admixture vanishes, and $\mathrm{H}_c = \pi/2$ as in pure CLC. For $\kappa \to \infty$ the concentrational redistribution becomes insignificant and $f \to f_0$. Fig.1 shows that in order to decrease the value of operated field, the dipolar orientational mechanism, corresponded to $\xi \gg 1$, has to prevail over the quadrupolar ($\xi \ll 1$) one. In this case FC is oriented by the magnetic grains and the so-called collective behavior [1] of a FC is realized. Such a behavior is characterized by a minimum concentration f_m of magnetic particles to orient CLC matrix. This concentration can be found from the condition $\xi \approx 1$ corresponded to the change of the orientational regimes from dipolar to quadrupolar one, i.e. $f_m = (q_0/M_s)\sqrt{K_{22}|\chi_a|}$. Above f_m the ferrocholesteric is oriented mainly by the magnetic particles and below – due to the existence of anisotropic

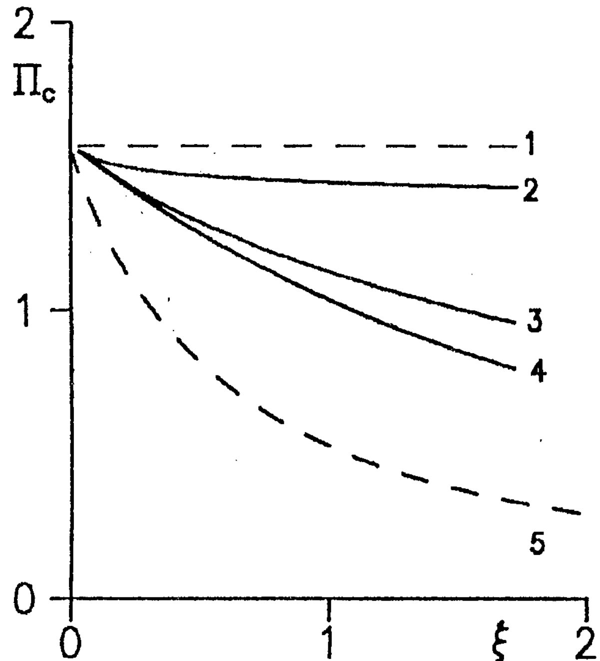

Figure 1: Critical magnetic field strength vs parameter ξ. Curve 1 — $\kappa = 0$, 2 — $\kappa = 0.1$, 3 — $\kappa = 1$, 4 — $\kappa = 10$, 5 — $\kappa = \infty$.

magnetic susceptibility of the CLC matrix. Putting $K_{22} \sim 10^{-7}$ dyn, $|\chi_a| \sim 10^{-7}$ cgs, $M_s \sim 10^3\,G$ and $q_0 \sim 10^4\,cm^{-1}$, we obtain $f_m \sim 10^{-6} \ll 1$, which is the correct order of magnitude (see [1]).

From Fig.1 one finds that ferrocholesteric – ferronematic transition occurs at any possible relation between the segregation length λ and the intrinsic pitch p_0 of the spiral structure, that is for arbitrary κ. However, the critical field is strongly decreased if $\kappa \gg 1$, i.e. without segregation effect.

Numerical simulations of the FC equations of state show that low field orients mainly the ferroparticles (since the susceptibility of the CLC matrix is too small) and due to the strong anchoring ($m \perp n$) between the particles and the molecules it gives rise to the distortion of the director field. Thus, the main particle axes m tend to align in the field direction, and the director n tend to be perpendicular to the field, corresponding to $m \perp n$ and $\chi_a < 0$, so the pitch of the spiral grows $p/p_0 = 1 + \xi^2\Pi^2/2$ and FC is being magnetized in the field direction $\langle M_y \rangle = \xi\Pi/2$. These results show that dipolar regime ($\xi > 1$) provides essential changes in the FC structure in comparison with the quadrupolar one ($\xi < 1$). In the vicinity of the transition point ($\Pi \leq \Pi_c$) the variation of the pitch and the magnetization becomes high. At the critical field Π_c the spiral structure is unwound and we have magnetically induced ferrocholesteric – ferronematic transition: $p \to \infty$, $\langle M_y \rangle \to 1$, i.e. all of the ferroparticles are oriented along the field.

If $\kappa \neq \infty$, then the ferroparticles are accumulated in those parts of the spiral structure where $m \parallel H$, and the so-called depleation layers appear where the particle concentration is strongly reduced. This segregation effect moderates the spiral unwinding (see Fig.1). When Π is close to Π_c, the region of favourable orientation for m and H occupies all over the greater part of spiral structure, the concetrational distribution tends to stepped kind and $f \to f_0$ at $\Pi \to \Pi_c$, so the magnetic grains become uniformly distributed over the sample in the ferronematic phase. The initial susceptibility χ of the FC is given by $\chi = |\chi_a|\,(\xi^2/2)(1 + 1/\kappa)$. Thus, in order to increase χ in a suspension dipolar regime ($\xi \gg 1$) and $\kappa \ll 1$ are required. For typical values of material parameters $M_s \sim 10^3\,G$, $f_0 \sim 10^{-5}$, $v \sim 10^{-15} cm^3$ and $T \sim 300\,K$, the susceptibility χ is about four or five orders of magnitude higher than χ_a for pure CLC.

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STRUCTURE AND PROPERTIES OF MAGNETIC FLUIDS

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Physic-chemical processes occurring in magnetic fluids (MF) are accompanied by different electric phenomena which may play an important part while forming one or another structural state in them. From this point of view it seems efficient to use dielectric spectroscopy methods to analyse the MF structure and properties [1].

In this work the changes in the value of dielectric permeability (ε), electric resistivity (ρ) and tangent of dielectric loss angle ($tg\delta$) of MF depending on the electric field frequency (10^2 -10^6Hz) and temperature (250-300 K) have been studied. MF based on kerosene by dispersed phase in which there is magnetite have been used, stabilisers are potassium soap of oleic acids and ascorbic acid.

The investigated samples were placed into a homogeneous a-c field generated in an interelectrode space of a measuring cell with plane-parallel electrodes made of stainless steel. The electric parameter values were taken from the digital display of impedance meters. The error in the electric parameters measurement is 0.1%.

A general tendency is the decrease of ε and ρ values which the increase of the electric field frequency whereas the value $tg\delta$ of MF first decreases (up to 10^3 Hz) then increases. The temperature dependence ε,ρ and $tg\delta$ of MF has maximum the position of which does not appreciably depend on the frequency whereas with the MF density increase it displaces towards lower T. The comparative analyses of the changes in the value ε,ρ and $tg\delta$ of MF depending on T has showed the most informative parameter to estimate the MF structure and properties is the dielectric permeability.

The analyses of these variations has shown that ε dependence at all registered frequencies. These changes were found to be comparatively negligible at high frequencies whereas at law ones ε value significantly increases with the decrease of T. The most significant changes of ε value depending on T are registered at the frequency 10^2 Hz. The presence of maxima for temperature dependencies $\varepsilon(T)$, $\rho(T)$, $tg\delta(T)$ for MF is explained by cluster formations displayed in MF under definite experimental conditions.

Thus the range of frequencies and temperature in which the electric parameters are most responsive to the change of the MF structure has been defined as the result of experiments done. This makes possible to use the dielectric spectroscopy method to analyse the MF structure and properties.

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Applications

ON THE OPTO-ACOUSTIC EXCITATION OF ULTRASOUND IN MAGNETIC FLUIDS

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This paper deales with investigation of opto-acoustic (OA) excitation of elastic waves in subsurface layeres of magnetic fluids (MF) and its using for science and practical application.

The generated laser radiation travels through the quartz prism, opposite part of which is immersed in MF, and then, penetrating into colloid, is absorbing within the depth up to $h \sim (2 \div 3)\alpha^{-1}$, where α is the light absorption factor. As a result of the layer heating, the elastic waves are emitted in straight and opposite directions. Wide band frequency ultrasonic transducer receives the acoustic pulses, and then transformed signal goes to amplifier and radiosignal spectrum analyzer inputs, restoring the time evolution of the pulse. In general situation of arbitrary laser pulse duration and imhomogeneous light absorption [1] the form of the OA signal in MF is described:

$$K_I^r = I_0 \int_{-\infty}^{\infty} f(\omega) e^{-i\omega t} d\omega \int_{-\infty}^{\infty} g'(\xi) d\xi \cdot D(c_p, c_0, \beta_T, \rho), \tag{1}$$

where I_0 is the laser radiation intensity, D- function, depending on the heat capacity c_p, density ρ. thermal compressability β_T and ultrasonic velocity of MF c_0. $g'(\xi)$ describes space distribution of the acoustic sources in solution at definite time τ, $f(\omega)$ characterizes the spectrum of the laser intensity function. Using (1) and the known program of the signal processing, it is possible to find out the light absorption coefficient and its depth distribution.

As follows from the laboratory findings, the dependence of normalized function $K_I^r(q)$ has a maximum independently on the dispersion base. Such behavior is explained by concurrence of the following dependencies: $\{c_p, c_0, \beta_T, \rho\} = F(q)$. Using (1), we restored function of the light absorbtion $\alpha(h)$. It should be noted that if $q<1\%$ and $h<h^*$, the light absorption in weak MF against q may be approximated by linear dependence. We find out that the curves $\alpha(h)$ have pronounced increasing with the depth of light penetration into MF if $h>h^*$, where h^* is the characteristic depth. The smaller the magnetic concentration, the longer the h^*. It is the evidence of complicated colloid structure formation near the interface [2,3]. The presented method was used to determine the continuous dependencies of the ultrasonic attenuation coefficient in magnetic fluids vs frequency. A possibility is shown to control the OA transformer function by external fields, and to use this effect in non-destructive testing.

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THEORY AND TECHNOLOGY OF THINNING SEMICONDUCTOR WAFERS USING MULTI-PHASE FERROMAGNETIC LIQUID

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In this paper we give the results of the theoretical and experimental studies of the technology of polishing (thinning) GaAs wafers, active (working) medium of which is a ferromagnetic fluid with small dispersed abrasive particles. The original method of processing described in the paper makes it possible by changing the induction of an external magnetic field to purposively control physical parameters of the process of polishing (thinning) and to get semiconductor wafers with high quality surfaces.

Mathematical descriprtion of the proceess in proposed, the results of which are in a good agrement with the experimental data. In every specific case they make it possible to propose optimal modes of processing. The equipment developed on the base of the conducted experiments allows to produce semiconductor wafers, the quality of which is essentially higher than the standard characteristics of the wafers proposed by the traditional methods.

APPLICATION OF THE MAGNETOFLUIDIZATION EFFECT IN PHYSIOTHERAPEUTICS

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Magnetofluidization is a specific range in ferrohydrodynamic and its promising application aspects are at the beginning stage. The real opportunity to organize a magnetically fluidized bed with stable dynamic characteristics - the intensive rotation-translational movement of magnetically hard particles in alternating magnetic field - has been appeared recently, although attempts to create some technical means based on magnetofluidization are known for a long time.

The rotational degrees of freedom of the magnetically hard particles are excited by the transferred part of external magnetic field energy and then their energy is redistributed in translational movement as a result of numerous interparticle interactions. At the induction of magnetic field up to 50 mT the maximal translational speeds of spherical particles with diameters 4-8 mm achieve 1.5 m/s, the rotational speeds several times exceed angular frequency of external magnetic field, the frequency of particle collisions with the unit area achieves 100 per second.

The employing of magnetically fluidized bed as a means for influence upon the chosen part of human body allows to provide essential massage effect coupled with another medicinal factors used in magneto-reflexotherapeutics. The merit of this method lies in the fact that all mentioned factors are interrelated and combined into single influence which comes under the cumulative and at the same time fine control.

The medical tests of the magnetodynamic massage equipment in clinics of Moldova have shown their high efficiency in treating of patients with bronchitis, bronchial asthma, ulcerous disease, chronic prostate disease, woman barrenness and stimulation of childbirth activities, some stomatologic illnesses etc. Moreover this equipment can be used for reabilitation after injury, for raising of creative activity and declining of tiredness.

MEASURING EQUIPMENT FOR MAGNETIC FLUID SYSTEMS ON BASIS OF HALL'S MICROSENSORS

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Technical characteristics of magnetic fluid devices are determined first of all by magnetic field parameters in zone where magnetic fluid operates. Magnetofluid systems have a range of special features which exclude for their research the use of standard measuring sets of magnetic field. Of known measuring systems the most compact are the systems on basis of Hall s sensors. But they also don't allow to measure magnetic field parameters in operation zone of magnetofluid seals (MFS). For MFS, it is typical operation zone compactness, thereat, minimal clearance is 50...150,mkm. Magnetic field has strong nonuniform character. Usuall Hall s sensors have dimensions of 2x1.5x0.6 mm with sensitive zone of 0.45x0.15 mm. These dimensions not only don t allow to arrange sensors in MFS clearance but also make impossible to measure field near it, as because of field high nonuniformity, induction in limits of sensor dimensions can change as 0.2...1 Tl. Therefore, main reguirements made to equipment to measure magnetic field in MFS are minimal dimensions of sensitive element and thickness of measuring probe of 50...70 mkm.

In this work it were successfully elaborated Hall s microsensors having sensitive zone dimensions of 0.05x0.05x0.02 mm and following technical data:

Range of measuring induction, Tl	10^{-2}...15
Sensitivity to magnetic field, mkV/mTl	30...150
Range of functional temperatures, ^{o}K	4.2...400
Feeding current, mA	5...25
Resistance of sensitive element, OHm	5...10

Microsensor advantages: small dimensions of sensitive element, wide range of functional temperatures, high time stability of characteristics.

On basis of microsensors it was made device to measure induction having transverse probe with length of 25 mm and thickness of 0.07 mm and axial probe with length of 100 mm and diameter of 0.8 mm. Such probe allows to determine parameters of magnetic field in clearances from 75 mkm and more with high resolving power. With the aid of this device it was studied topography of magnetic field along shaft surface in MFS, it was determined magnetic field changement along shaft circle which is caused by eccentricity; it were carried out studies of sealing unit temperature effect on field in clearance.

For the purpose of diagnostics of magnetic fluid stability in nonuniform magnetic field it was elaborated a device with twin Hall s microsensors.

Besides works of research character the device allows to fulfil, when operating, control of sealing magnetofluid systems by field parameters.

MAGNETOFLUIDIC SENSOR FOR DENSIMETRY

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The substitution of a magnetic fluid which has a hight value of the magnetic susceptibility with a nonmagnetic body in the inner side of a coil lead to change coil's inductance. This is the essential principle of the sensor, which consist of a diamagnetic or paramagnetic cilindrical vessel surrounded by a coil on half of its lenght. Laying in the vertical position the bottom half of the vessel is filled with magnetic fluid which will be located in the inner side of the coil. The top half of the coil is empty. It is well known that the inductance of a coil is a function of the magnetic permeability of the material located in its inner side. If inside of the coil is only magnetic fluid the inductance will be $L = L(\mu_{MF})$ where μ_{MF} is the magnetic permeability of the magnetic fluid and may be expressed thus $\mu_{MF} = \mu_0(1+ \chi_{MF})$ where μ_0 is the magnetic permeability of the vacuum and χ_{MF} is the magnetic susceptibility of the magnetic fluid.

If a nonmagnetic body which possess a density $\rho_B > \rho_{MF}$ where ρ_{MF} is the density of the magnetic fluid, is introduced in the vessel, it will replace a fraction f of the magnetic fluid from inner side of the coil so that the level of the magnetic fluid will rise in the vessel. In these conditions magnetic permeability of the material located inside of the coil becomes $\mu = f\ \mu_B + (\ 1- f)\ \mu_{MF}$ where μ_B is permeability of the body and $f = V_B / V_{MF}$ where V_B is volume of the body and V_{MF} of the magnetic fluid equal with volume of the bottom half of the vessel located inside of the coil.

Finally the inductance of the coil may be expressed as a function of the volume of the body $L=L(V_B)$. If the weight of the body is known it is easy to obtain $L=L(\rho_B)$. A theoretically analysis and some experimental results about this sensor will be presented in paper.

MENISCUS SHAPE AND SPLASHING OF MAGNETIC FLUID IN MAGNETIC FLUID SEAL

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1. Introduction Magnetic fluid seals are successfully utilized as spindle seals for magnetic disk storage to protect the head-medium interface from dust-caused damage. The upper limit of the rotational speed is limited by the centrifugal force-induced splashing of magnetic fluid from the gap. The present study was undertaken to clarify further the splashing mechanism in relation to meniscus deformation due to fluid rotation.

2. Simulation To determine the free surface shape of the magnetic fluid, the SMAC (Simplified Marker And Cell) method is extended to involve additional forces acting in/on the magnetic fluid, such as magnetic force, centrifugal force and surface tension. The magnetic field is first calculated, followed by transforming into an SMAC field through interpolation which permits different grid patterns to be adapted between the two. As for centrifugal force distribution, a rotating seal is selected instead of a rotating spindle. The force is then assumed to increase linearly from the gap innerside at rest to the gap outerside during rotation, and to increase further with rotational radius on the yoke. The initial surface shape is configured to be triangular. At the first stage, centrifugal force is neglected to obtain the solution at rest. Using this solution as the initial shape for the rotating condition, the second-stage calculation is performed considering centrifugal force.

Typical calculation results are demonstrated in Fig. 1. From this figure, the meniscus is observed to be asymmetrical due to the gravity force being directed downward and to be dragged outwards with the increasing rotational speed.

3. Experiment The meniscus shape during seal rotation was measured using its shadow as it was being illuminated with a laser beam. The shadow was taken with a high-speed CCD camera as image data. Applying image processing to the data obtained, a surface cross-sectional curve was clearly obtained as is indicated in Fig. 2. The surface curves measured for various speeds are also superimposed in this figure. As is evident, when the speed increases, the magnetic fluid moves outerwardly induced by centrifugal force. With a further increase in speed to above 1400 rpm, sudden shrinkage of the surface occurs as noted by the dotted line. This corresponds to the splashing occurrence hidden at the downside of the yoke, which qualitatively accords well with the calculation results.

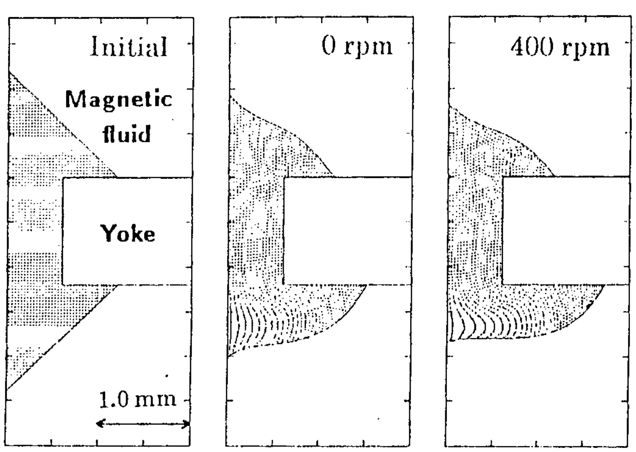

Fig. 1 Calculation results demonstrating deformation of magnetic fluid surface

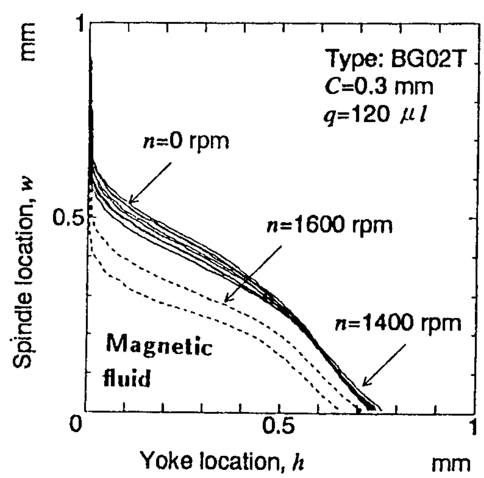

Fig. 2 Meniscus shape cross section observed at each 200-rpm increment.

PHYSICAL PRINCIPLES OF MAGNETIC FLUID SEAL BEHAVIOR AT HIGHER TEMPERATURES

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Magnetic fluid seal (MFS) application is bound with device temperature changes what is units turn bound with environment temperature ones (-40...+40°C), technological equipment heating up, inner heat releases caused by viscous friction in magnetic fluid (MF). Heating-up as a result of conciderable inner heat releases is typical for high-speed seals.

Temperature elevation causes the following physical processes. First, there are changed magnetic properties of magnetic system materials: pole pieces steel, permanent magnets, magnetic fluid. As a result it is changed magnetic field in working gap of the seal and interaction forces between magnetic field and magnetic fluid, i.e. under temperature action seal holding capacity is essentially changed.

Second, on temperature it depends seal friction torque what is caused by the following factors: magnetic field intensity change which determines particles interaction forces within magnetic fluids (MF) and viscosity change.

Third, temperature influences on MFS service life. At elevated temperature permanent magnets ageing is accelerated, i.e. reduction of their magnetization as well as, what is more important, there is MF intensive ageing.

At temperature elevation it is intensified magnetic fluid base evaporation. Temperature elevation above critical one leads to surfactant desorption off magnetic particles. This process leads to aggregation and sedimentation of MF and as a result to MFS failure.

To determine temperature effect on given physical process experimental complex investigation was carried out.

Experimentally determined was temperature effect on magnetic properties of used steels, permanent magnets, magnetic fluids in span of +20 ...200°C. Of magnetic fluids there were studied some marks produced by our Laboratory of MK-2-40 type on polyethylsiloxanic carrier PES-4, MK-1-25 type on basis PES-5 and MK-8-40 on basis of transformer oil.

Obtained data were used in mathematical model of MFS magnetic system at calculating of magnetic field in a gap. It was shown depending on used materials stresses differential of magnetic field under seal pole pieces at temperature elevation to 150°C is reduced by 30% and more. Taking into account MF magnetization reduction, held pressure differential may reduce to 40% and more, what is verified by experimental studies. Magnetization reduction in MFS in observed changes of friction torque is not determinative.

Experimentally studied was temperature effect on MF rheology. Temperature elevation , as known, leads to colloid system viscosity decrease provided thereat no irreversible structural phenomena happen.

Depending on MF type, viscosity changes 3 ...10 time as much as temperature increasing from 20 to 150°C. Thereat, note should be taken that magnetic colloids elaborated in our Laboratory,

prepared on magnetite of aqueo-organic media retain Newtonian properties and temperature dependence of viscosity in similar MF a wide range of magnetic filler concentrations practically coincide with such dependence for clean carrier. This tells about that MF obtained by non-traditional method approximates to homogeneous fluid while MF with magnetite prepared acc. to conventional technology has viscosity wich reduces at temperature elevation especially strongly.

Structural viscosity disappears at temperature of 55°C. For similar structurizated colloidal systems rheology is not described by Newton's Law and viscosity depends both on temperature and shear speed.

Physico-chemical processes proceeding in MF at heating are studied by thermogravimetric and infrared-spectroskopic methods. Carried out are derivatographical studies of some organic carriers liquids, hydrocarbonic acids and magnetic fluids with the aim of determination of specified temperatures at which qualitive and quantitive changes of samples are observed.

Derivatograms are read in 20 to 500°C temperature interval, heating speed 10 °/min, measurement accuracy 0.2%. For carrier fluid PES-4 up to temperature of 150°C there are observed no changes, then to 200°C a slow loss in weight and afterwards a rapid sample decomposition.

The most resistant to temperature elevation is carrier of mark PMS-100 which withstands temperature elevation to 250°C without any changes and only heating to 340° brings to full sample decomposition.

At examination of magnetic fluid temperature stability according to carried out derivatographic studies of MK-2-40, MK-8-40 withstand fast equally temperature loads to 130...140°C at full absense of changes on curres, then a slow loss in weight to decomposing initiation temperature onset of 180...200° caused by evaporation intensification. Evaporation speed at such temperatures varies within the limits of $(0.6...6.5)10^{-6}$ $g/cm^2 sec$.

With temperature elevation there begin rapid processes of carrier oxidation what leads to increasing loss in weight and MF polimerization. MF full decomposition ensues at about 300°C.

Infrared-spectroscopic investigations showed that oxidation processes in some MF (mainly on hydrocarbonic carrier) change also character of magnetic dispersive particle interaction with surfactant what leads to evident power oxidation with surfactant and a result thereof to MF magnetization loss.

Processes proceeding in MF at heating change somewhat their character when MF is a part of MFS. Therefore,it were carried out studies of temperature influence on magnetic fluid seals service life. It is shown that MFS operation without forced cooling is possible to 90...100°C.

ON THE STABILITY OF A STATIC MAGNETOFLUID SEAL UNDER THE INFLUENCE OF A PRESSURE DROP

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A magnetofluid seal (MFS) in a narrow profiled gap between two co-axial motionless cylinders is considered. The outer cylinder is supposed to be an annular permanent magnet with a hyperbola-shaped concentrator of magnetic flux. The idea of such a gap profile belongs to A.N.Vislovich. Under the assumption that magnetic fluid is in the saturation state and solid walls are of high magnetic permeability, magnetic field in the gap is described by simple analytical formulae. A numerical study of the deformation and disruption of the magnetofluid plug under the influence of external pressure drop, magnetic and capillary forces has been undertaken in [1]. Main purposes of the present work are to carry out the numerical investigation in more wide parameter range and, to find analytical solutions of the simplified problem when capillary effects are neglected.

The determining parameters are $Bo_m = \mu_0 M_s H_{max} a/\sigma$, the magnetic Bond number; $Pm = \Delta p/(\mu_0 M_s H_{max})$, the parameter characterizing pressure forces with respect to magnetic ones; $U = \Omega/a^2 \approx V/(2\pi a^2 R)$, the dimensionless volume; α, the wetting angle; β, the half-angle between asymptotes of the concentrator hyperbola. Here μ_0 is the magnetic constant; M_s, the saturation magnetization of the fluid; H_{max}, the magnetic intensity magnitude in the pole-piece point; σ, the surface tension coefficient; Δp, the external pressure drop; Ω and V, the axial-section area and the volume of the magnetofluid plug; R, the inner cylinder radius; $a \ll R$, the gap width.

Evolution of the free surface as Pm increases is studied numerically. Critical values $Pm = Pm_c$, on exceeding of which the sealing layer undergoes disruption, are determined for $200 \leqslant Bo_m \leqslant 1000$, $1 \leqslant U \leqslant 20$, $0 < \beta < \pi/2$, $\alpha = \pi/4, \pi/2, 3\pi/4$. An exact solution of the problem is found in the limiting case $Bo_m \to \infty$. It is shown that at $Bo_m \geqslant 400$ the critical parameter Pm_c does not depend practically on Bo_m and is determined by "volume" U only. At $\beta = \pi/4$, $2 \leqslant U \leqslant 20$ this dependence is described with the error less than 2% by the formula

$$Pm_c = A - \left(2 + B\,\tilde{U}^n \right)^{-1/2}; \quad \tilde{U} = U - 0.45, \; A = 0.707,$$

$$B = \frac{8}{\pi} \left(1 + 2.5/\tilde{U} \right)^{-1}, \; n = \left(1 - 0.3/\tilde{U} \right)^{-1}.$$

The study is supported by the funds from the Foundation of Fundamental Research of the Republic of Belarus.

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ON THE FORMATION AND CONTROLLING OF THE MAGNETIC FLUID SURFACE AND ITS USING IN ACOUSTIC FOCUSING

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We study the features of the magnetic fluid ultrasound lines formation by ponderomotive and gravity forces, and influence of free surface form on the expendable characteristics of ultrasound transducers. The equilibrium forms of the magnetic fluid (MF_1) placed on the magnetized semi-infinite solid with magnetic permeability μ, arrounded by MF_2, and held by applied magnetic field of one or several magnets, are studied. The modified Bernully equation and approximation of heavy liquid [1,2] is used. Let MF_i is magnetized by law $M_i=c_i(k)H^k$, $(1\le k\le 2)$ and sound pressure P_u acts on the fluid interface boundary (MFB). The phase pictures of the MFB evolution investigated depends on the following parameters:

$$S_k = (2md)^k c_i(k) I_k (\Delta\rho g)^{-1} h_0^{-k}, S_a = P_u(\Delta\rho g h_0)^{-1}$$

I_k is a constant, $\Delta\rho$ is the difference of fluids density, m is a volume magnetic moment of the magnet, h_0 is the height of magnets, d-width. We generelize the results of [2,3].

It is shown that the evolution of MF equilibrium forms follows in another way when a magnetized solid is. If $\vec{m}\perp z$, two peaks of MF_1 arise and grow with the increasing of magnetic field, created by equivalent system of conductors with currents flowing in parallel directions. If $S_1\ge S_k^*$ MF_1 abruptly encloses the lower one (or several) conductor and captures MF_2 volume. This evolution process is repeating with the further increasing of magnetic field. For currents flowing oppositely the evolution pictures are different. If $\mu=1$, $d/h_0<<1$ and the other magnet sizes are large the MFB instability occurs, when the height of the unique peak $z_k = 1/(k+1)$ and $S_k^*=[1-1/(k+1)-S_a]/[1+k(k+1)+S_a]$. If $\mu>>1$, S_k^* increases for two times.

A number problems of the MF acoustic lens holding in applied magnetic field with the axial and central symmetry are solved. Varying S_k and angle φ between $\vec{g}$ and acoustic axes z, it is possible to get the best focussing characteristic of the acoustic lens. If $g\perp z$ and $S_k<S_k^*$ the smaller the S_k the the shorter the focus. Maximal acoustic aberration is done when $\vec{g}\perp z$. The ultrasonic transducers, operating in frequency range from 2.5 to 10MHz with MF quasi-spherical and quasi-cylindrical focusing lenses, have been designed and investigated. As follows from the first laboratory findings the obtained focusing characteristics of MF lenses are not worse than the traditioanl focalizers have [4]. Unlike the known liguid lenses, the curvature of which is changed by external pressure, in the proposed method MF-NF boundary formation is controlled by volume forces. In so doing a new form of the MF-NF boundary and its correction can be obtained by the new different methods.

This work was supported by the Found of Fundamental Investigations of Republic Belarus.

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HYDRODYNAMIC MODEL OF MAGNETIC FLUID SEALS

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High antifriction properties of magnetic fluid seals (MFS) are determined first of all by rheology of magnetic fluid (MF) and it stability against effect of nonuniform magnetic field under whose action operation-technical characteristics of devices are changed, service life is reduced.

In a common case, MFS hydrodynamic model contains a range of strong non-linear media: non-uniform gap of complex geometric shape in friction zone, complex topography of nonuniform magnetic field, non-linearity and time non-stationarity of magnetization M(H), as a function of time, and non-stationarity of effective viscosity $\eta(H)$ in nonuniform magnetic field by process of local concentration redistribution.

At first it was considered mechanism on forming of hydrodynamic flow in MFS friction zone at quasy-static conditions(at absence of MF redistribution process in MFS friction zone). In cylindrical coordinates for axially symmetric single component MF flow and for viscoplastic rheology model it was obtained the following equation:

$$- \vartheta_\Phi^2/r = - (1/\rho)\cdot d\Delta P/dr + M_r\cdot(1/r)\cdot d(rH_r)dr_r + M_z\cdot dH_z/dr$$
$$0 = \eta\cdot d/dr(d\vartheta_\Phi/dr-\vartheta_\Phi/r) + \eta\cdot d/dz(d\vartheta_\Phi/dz) +$$
$$+ (2\cdot\eta/r)(d\vartheta_\Phi/dr-\vartheta_\Phi/r) + 2\cdot\tau_o/r\cdot sign(d\vartheta_\Phi/dr - \vartheta_\Phi/r)$$
$$0 = - d\Delta P/dz + M_r\cdot dH_r/dz + M_z\cdot dH_z/dz \qquad (1)$$

where $\eta(H)$, $\tau_o(H)$- rheological parameters MF as a function of magnetic field from magnetoviscometry.

Because of hydrodynamic equations are rather complicated for the considered MFS friction zone the problem is calculated numerically on PC/AT by means of finite elements method. As calculation region it is taken a gap area corresponding to one elementar pole of pole piece zone in which it is placed non-symmetrically under action of outer pressure difference ΔP magnetic fluid plug. As a result of numerical calculation it is found distribution of speeds and speed gradients at the following boundary conditions: on immovable surface of pole $\vartheta = 0$, on surface of rotating shaft $\vartheta = \vartheta_o$ and a condition for balance of stress on free surface of magnetic fluid plug $(d\vartheta_\Phi/dn=0)$, where n - vector of normal to free surface.

Shaft friction moment is determined from the folloving equation: $M_{fr} = \int|\tau_{r\Phi}|_{r=R}\cdot R\cdot dS,$ (2)

$$\tau_{r\Phi} = \tau_o(d\vartheta_\Phi/dr - \vartheta_\Phi/r)/|d\vartheta_\Phi/dr-\vartheta_\Phi/r| + \eta\cdot(d\vartheta_\Phi/dr-\vartheta_\Phi/r)$$
$$M_{fr} = \int |(d\vartheta_\Phi/dr - \vartheta_\Phi/r + (\tau_o/\eta)sign(d\vartheta_\Phi/dr-\vartheta_\Phi/r)|_{r=R}\cdot\eta\cdot R\cdot dS$$

Approximation error of numerical calculation result is determined by conditions of speed transverse components disregards such as $\vartheta_r/U\approx(\delta/R)^{0.5}\ll1$, thereat, disregard conditions to concrete members is determined as $Re\cdot(\delta/R)^{0.5}\ll1$, $(M\nabla H\sim10^3\rho g,\ M\nabla H\gg\rho\vartheta^2/r$ $\vartheta\leqslant5$м/с)/1/. Considerable deviation of experimental points from calculated ones in this approximity may be explained by change of rheologic and magnetic properties in MFS friction contact zone under the effect of the force $F = M\nabla H$ leading at MFS long-term service time, as a result of magnetic sedimentation, to difference with initial rheological parameters taken as a calculation base in equation (1), (2).

Experimental data for checking truth of calculation-experiment methodics of MFS friction torque forecasting are obtained by

using a special experimental stand MFS geometry parameters are analogeous to calculated zone friction ones and are as follows: shaft radius 34 mm, shaft rotation speed 0.1...0.5 m/s, optimal MF volume 0.368 cm^3, pole piece thickness 3 mm, pole piece angle 45^o, height of gap 0.2 mm. Equipment allowed to measure set friction torque in dinamics and start-off torque as well as relaxational transient process of friction torque dependence on time at starting-off.

For obtaining more trustworthy forecastings it was worked out calculation-experimental methodics based on MF main operational parameters obtained from diagnostics of MF stability of dynamics-in-time approcximational models: friction torque and punch pressure in nonuniform magnetic field. It was considered MFS friction torque forming mechanism when load force $F(t)=M(t)\nabla H$ on friction contact depends on delay time in field because of increasing of local magnetization $M=M(t)$ under pole pieces ridge.

Taking into account time dynamics of redistribution processees for forecasting of friction torcue and punch pressure it was proposed to use approximational model dependences as follows: $\Delta P(t)=\Delta P_o+(\Delta P_m-\Delta P_o)\cdot(1-\exp(-\alpha\cdot t^{0.5})$, $M(t)=M_o+(M_m-M_o)\cdot(1-\exp(-\beta\cdot t)$ where ΔP_o- initial punch pressure to be determined by means of approximation of experimental dependence $\Delta P(t)$ into region of small times ($t_o<_5 10^4$ sec) in limits of Taketomi's model $\Delta P(t)=\Delta P_o*(1 + K_t*t^{0.5})$ on PC/AT, maximal pressure ΔP^{max} was found by approximation of finite time part of $\Delta P(t)$. Analogously, parameters of friction torque M_o^{fr} and M_{max}^{fr} were found by approximation of initial and finite time part of experimental dependence $M^{fr}(t)$.

With the purpose of further improving the accuracy of calculation-experiment method of MFS friction torque forecasting it was examined MFS hydrodynamics forming mechanism on basis of magnetoadhesional component of magnetoviscous effect(MVE). It is shown, that in case of MF frictional contact with ferromagnetic thin-layered coating on shaft, MVE increases by 15...20% in comparison with non-magnetic thin-layered coating/2/. In case of viscoplastic character of inner hydrodynamic friction it is necessary to take into account magnetoadhesional component of plastic viscosity η^{adh} and initial shear stress τ_o^{adh}.

Calculations on proposed model describe friction moment change mechanism only in the case when rheology parameters found experimentally are knoun with sufficient accuracy taking into account temporal dynamics of MF characteristics change in inhomogeneous magnetic field. Reduction and realization of minimal friction in MFS are possible to carried out studies on account of magnetoadhesional effect reduction into summary friction torque at application of non-magnetic coatings on ferromagnetic details of MFS magnetic circuit and on accountof effect reduction of MF redistributing process and temporal non-stability of MF characteristics in inhomogeneous field.

Furthermore, mechanism of inner friction itself plays important role in MFS antifriction characteristics increasing evident advantages over viscoplastic fluids there possess magnetic fluids with Newtonian properties ($\tau_o\to 0$) and low coefficient of redistribution of thise parameters in wide range of nonuniform magnetic fields.

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THE DISSIPATIVE HEAT-UP OF MAGNETOFLUID SEALS

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A factor limiting the sphere applicability of magnetic fluid seals is the heat-up of the fluid because intensive shift flow. Rectilinear Couette flow of the newtonian fluid with constant coefficients of transfer in the gap of constant width (simple shear flow) is the basic model for an evalution of thermohydrodynamical parametrs in these devises [1,2]. The temperature dependence of transfer coefficients, the gap shape and the shape of fluid free surfases have an influence on the seal thermohydrodynamics. These problems are considered in [1,2] on the base of coars geometrical and physical assumptions.

In the present work these problems have been solved on the base of exact theory. We consider the rectilinear steady flow of an viscous fluid along some axis z. The flow is indysed by relative movement of two solid boundaries. Their normal to axis z sections are arbitrary curves $l^{(0)}$ and $l^{(1)}$. Their velocites are v_0 and v_1, temperatures are T_0 and T_1 $(T_0<T_1)$, respectively. The conditions of mechanical equilibrium and heat insulation are fulfiled on fluid free surfases $l^{(S)}$. The problem geometry is shown in Fig.1. The mathematical formulation of the problem can be written in the following way

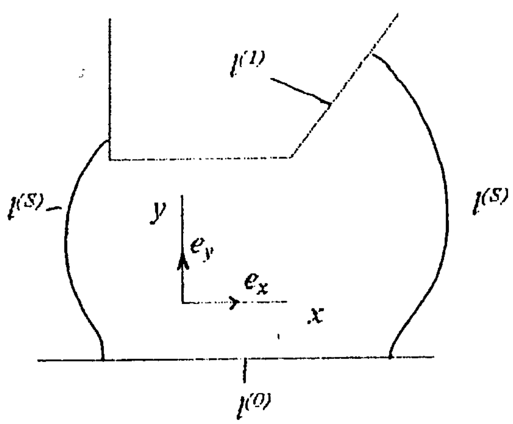

Fig.1

$$
\begin{aligned}
&\nabla\cdot\vec{p}=0, \quad p_n\big|_{l^{(s)}}=0, \quad \nabla\cdot\vec{q}=-\vec{p}\cdot\nabla v, \quad q_n\big|_{l^{(s)}}=0,\\
&\eta\nabla v=-\vec{p}, \quad v\big|_{l^{(0)}}=v_0, \quad v\big|_{l^{(1)}}=v_1,\\
&\lambda\nabla T=-\vec{q}, \quad T\big|_{l^{(0)}}=T_0, \quad T\big|_{l^{(1)}}=T_1,
\end{aligned}
\tag{1}
$$

were $\nabla=\dfrac{\partial}{\partial x}\vec{e}_x+\dfrac{\partial}{\partial y}\vec{e}_y$; $\vec{q}$ and $\vec{p}$ are densities of a heat flux and a diffusion momentum flux, respectively; λ and η are coefficients of thermal conductivity and shear viscosity, respectively.

This model determins the similarity of a temperature and a velocity isolines. It does possible the general investigation of the problem. The result of exact solution of the system (1) is the following equation

$$
\frac{2}{v_*^2}\int_{T_0}^{T_m}\frac{\lambda}{\eta}\,dT=\frac{1}{4}\left(1+\frac{2}{v_*^2}\int_{T_0}^{T_1}\frac{\lambda}{\eta}\,dT\right)^2. \tag{2}
$$

It defines unexplicitly the maximal temperature T_m in the fluid volume. This equation does not involve geometrical characteristics. It holds true for arbitrary gap profile and the shape of fluids free surfaces. The dissipative heat-up T_m - T_0

depends on relative velocity $v_* = v_1 - v_0$ and character of temperature dependence of value $\lambda/\eta = f(T)$.

By same boundaries temperatures $(T_0 = T_1)$ (2) is simplificed:

$$\int_{T_0}^{T_m} \frac{\lambda}{\eta}\, dT = \frac{v_*^2}{8}.$$

In addition, in this case it follows from the theory that across each solid boundary remove exact half of dissipative heat.

The heat up reaches the largest value if on solid bounda ry (for example on $f^{(1)}$) the condition of heat insulation is valid. Setting $T_1 = T_m$ we have from (2) for this case:

$$\int_{T_0}^{T_m} \frac{\lambda}{\eta}\, dt = \frac{v_*^2}{2}.$$

Let us present an useful example of solution of equation (2). Setting $\lambda = const$, $\eta = \eta_0\, exp\,[-b\,(T - T_0)]$ we have

$$T_m - T_0 = \frac{1}{b} ln \left\{ 1 + \frac{b\vartheta_*}{2} \left[\frac{1}{2} + \frac{\vartheta_1}{\vartheta_*} \frac{exp\,(b\vartheta_1) - 1}{b\vartheta_1} \right] \right\},$$

where $\vartheta_1 = T_1 - T_0$, $\quad \vartheta_* = \eta_0\, v_*^2/\lambda$.

The model (1) does not take into account nonlinearity and anisotropy of transfer processes and secondary flows. They can have an effect on dissipative heat-up of real seals. These factors are disturbed the similarity themperature and velocity isolinies and hinder the universally theoretical analys. The influence of these factors is considered on base of phenomenological consepts.

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Late Presentations

USING OF COMMERCIAL PROGRAM COORDINATOR (MAGNETO-ELECTROSTATIC DIFFUSION AND THERMOCONDUCTIVITY) FOR SOLUTION OF MAXWELL EQUATIONS BY CALCULATION OF MHD INDUCTION SYSTEM

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While high cost of commercial computer programs for calculation of vectorial AC electromagnetic fields and eddy currents in liquid metals make unavailable they for wide using between researches of former Soviet Union. The simple method of magnetic permeability correction suggests in article. The idea of method consists in aim-direction change of magnetic permeability of space, where the solution is found. It permit, for example, to decrease the penetration of direct magnetic field into electroconductive space like by classic skin-effect. In this case the space that has the magnetic permeability of vacuum ($\mu_0 = 4\pi * 10^{-7}$ Hn/m, $\mu = 1.0$) receives the one $\mu > 1$.

Some testes and well know tasks are shown in article. The compares of solutions was suggested.

FILM FLOW OF LIQUID METAL ON FERROMAGNETIC WALL IN TRANSVERSE ALTERNATING MAGNETIC FIELD

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Film flow creates on vertical steel sheet or strip by coating of it by Zinc or Aluminum alloys in liquid metal pull. The problem of control thickens of coating-layer was soluted in suggested article. Electromagnetic forces created in Zn or Al layer on surface of steel sheet. They made a shape of free surface of Zn, Al film on the sheet.

In the article the shape and AC magnetic field parameters was correlated. The liquid metal film was assumed laminar, but electromagnetic forces were calculated with accounting of current v*B*σ, that was created by movement of sheet and film in magnetic gap.

It was show, that typical thickness of Zn (Al) layer could be decrease from 1 mm to 0.1 mm.

SEMIEMPIRICAL THEORY OF TURBULENCE FOR CONDUCTIVE FLUID IN A MAGNETIC FIELD

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Turbulence flow of electroconductive fluid in a magnetic field is described by the set of equations for mean parameters in the same manner as Reynolds equations. Turbulence pulsations in a flow are anisotropic even in the absence of a magnetic field as it follows from many experiments. For this reason semiempirical theories like k-e models where anisotropy is not taken into account may follow to incorrect results.

In the present paper the semiempirical theory based on the set of equations for second moments of velocity and induced magnetic field pulsations [1] is developed. These equations contain terms described advection, diffusion, generation and exchange pulsations between axes. In a semiempirical theory it is necessary to use approximations for dissipative and exchange terms. For dissipation we can use known approximations which have been checked in many cases of comparison theory and experiments. The main problem consists of approximation for exchange terms which are responsible for anisotropy and rearranging pulsations in different axes. These terms are presented by correlations of pressure and vorticity pulsations. The relaxation type approximation for exchange terms has been used before and the influence of mean velocity gradient and volume forces has not been taken into account.

In this report for pressure pulsations the exact Poisson equation which follows from Navie-Stokes equation is used. General solution of this equation is found and it is used for calculation the second moments of velocity and magnetic field. After averaging procedure the exact representaion for exchange terms are found. They contain terms proportional to gradient of mean velocity and volume electomagnetic forces. For gravity forces this approach has been developed in [2]. The same approximations for exchange terms in all equaitons are used. Using general properties of second moments which follows from symmetery, continuity and solution of the Poisson equation by Green function method give a very strong result that this theory contains just one semiempirical parameter. This parameter has been defined from comparison presented theory with experiments in tubes and in boundary layers.

As a result the closed set of equations has been found. The developed theory can be applied to any case of turbulence flow of conductive fluid in a magnetic field at low Reinolds number. General theory has been applied to the boundary layer with the longitudinal and transversal magnetic fields.

This work has been partially supported by the International Science Foundation and authors are thanked to the Foundation.

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Experimental investigation of the homogenous Dynamo-effect

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Abstract:

In this article a laboratory experiment for a homogeneous dynamo based on a sodium flow is proposed. The design utilises the dynamo concept based on separation of scales as proposed by Roberts and Busse, which takes its simplest form in spatially periodic dynamos. The design incorporates nearly periodic small scale helical motions in a sodium filled cylindrical box. Critical magnetic Reynolds numbers for the spontaneous magnetic field excitation are derived in an improved analytical model. In this model the influence of the convection of the magnetic field as well as the diffusion of the magnetic field into the outside region of the magnetic field generating domain are included. Additionally boundary conditions taking into account the finite geometrical extension of a laboratory experiment and their influence on the critical magnetic Reynolds number are discussed. The incorporation of the additional terms and the introduced boundary conditions in the model lead to an enhanced diffusion of the magnetic field, which consequently yields a higher magnetic Reynolds number to achieve self-excitation of the magnetic field.

The main features of the improved model as well as the technical consequences concerning a laboratory experiment are outlined. Also some results of a water experiment for the main element of a periodic dynamo, the spin-generator, are presented.

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